A DISCRETE-EVENT SIMULATION MODEL FOR EVALUATING AIR FORCE REUSABLE MILITARY LAUNCH VEHICLE POST-LANDING OPERATIONS

GRADUATE RESEARCH PROJECT

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Abstract

The United States military, and in particular the Air Force, has long recognized the requirement for a responsive spacelift capability as an enabler to gaining and maintaining space superiority. In order to fulfill this requirement, the Air Force as a portion of its Operationally Responsive Space initiative is considering the design and development of a reusable military launch vehicle (RMLV) to provide more responsive spacelift than the current spacelift systems provide. The design of both the RMLV and the supporting ground processes will determine whether the Air Force can successfully achieve its performance goals for the RMLV. The purpose of this research was to develop a discrete-event computer simulation model of the post-landing vehicle recovery operations to allow the Air Force Research Laboratory, Air Vehicles Directorate to evaluate design and process decisions and their impact on RMLV regeneration time in the early phases of the acquisition process.

The model is based primarily on the post-landing vehicle recovery process for the only reusable space vehicle in the world, the Space Shuttle Orbiter. However, it does contain some elements from the aircraft recovery process for the F-16 fighter aircraft. The model was analyzed and validated by a panel of experts in the fields of Space Shuttle Orbiter and F-16 aircraft post-landing recovery. The model was verified using an assertion checking method. In addition to the model, conclusions are drawn regarding several design decision based on a comparison of the Space Shuttle orbiter and F-16 post-landing recovery operations. No experiments to evaluate design alternatives were conducted as a part of this research.

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Michael Martindale

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A DISCRETE-EVENT SIMULATION MODEL FOR EVALUATING AIR FORCE REUSABLE MILITARY LAUNCH VEHICLE POST-LANDING OPERATIONS

I. Introduction

Background

The United States currently enjoys the considerable advantage of owning and operating the best military space capabilities in the world. Capabilities such as secure global communications provided by our military and commercial communications satellites, and precise navigation and timing available from the Global Positioning System (GPS), have allowed the Air Force and the entire Department of Defense (DoD) to fundamentally change the way America fights wars. The advantages gained from these and other space capabilities are so profound that the Air Force has had to develop the new doctrinal concepts of space superiority and space supremacy. Gaining space superiority is a critical step in any military operation, and provides sufficient control of space in ensure freedom of action for friendly forces, to include the freedom to attack as well as the freedom from attack (AFDD1:76). Space superiority provides the degree of dominance to "permit friendly…space forces to operate at a given time and place without prohibitive interference by the opposing force" (AFDD1:77). Space supremacy goes a step further, providing the "degree of superiority wherein the opposing…space forces are incapable of effective interference anywhere in a given theater of operations" (AFDD1:77). Like air and land superiority, space superiority is a critical element of the American way of war.

There are several capabilities that are required to deliver the effects needed to ensure space superiority, including timely and responsive spacelift. Air Force spacelift objectives are to "deploy new and replenish space assets as necessary to meet US space goals and achieve national security objectives" (AFDD1:52). In meeting these objectives, the Air Force must provide spacelift capabilities that are functional and flexible, capable of meeting a full range of national security requirements, in a manner that is timely and responsive to the user's needs (AFDD1:52). In simplest terms, the Air Force's spacelift capabilities must be able to reliably deliver a broad variety of capabilities to orbit in a timely and responsive manner. If the Air Force's spacelift system cannot deliver a variety of different satellites, with varying capabilities, to space when they are required, the Air Force will not be able to meet its spacelift mission requirements.

Current expendable launch systems, while reliable, are not responsive, often taking weeks to months to prepare for launch (Isakowitz et al, 2004:496). To provide a more responsive launch system, at a lower cost, the Air Force is conducting research to develop a reusable military launch vehicle (RMLV) within the construct of Air Force Space Command's concept for Operationally Responsive Space (ORS), a subset of which is Operationally Responsive Spacelift (Stewart, 2003).

The National Aeronautics and Space Administration's (NASA) Space Shuttle is the only reusable space launch vehicle currently in use worldwide. Researching the design, methods, and processes for operating and maintaining the Space Shuttle Orbiter provides a baseline for the RMLV, but it is not a perfect match. The Space Shuttle, while accomplishing impressive feats, never met its operational performance goals for the

number of expects flights per year. A major factor in the failure to reach its goals was the complexity and duration of the ground operations required to recover the orbiter and prepare it for its next mission (McCleskey, 2005:2-3). In its root cause analysis to determine areas for technical process improvement, NASA identified numerous causes for the length of the vehicle turnaround time. Most of these causes were the result of the systems design features, such as: the use of hazardous fuels and pyrotechnics that require special handling to protect personnel, complex maintenance processes that could potentially be simpler with a different vehicle design, and maintenance processes that required additional work simply to access the item due to structural design (McCleskey, 2005:77-119). The Space Shuttle as a system has been reliable, but it has not provided the responsiveness and performance it was intended to in its original conception.

The implication of the performance limitations of the expendable launch systems, and the only reusable launch system for the RMLV designers is clear: RMLV designers must learn from the experiences of past space launch systems, and apply the lessons to the RMLV's design to ensure it can meet the performance goals defined by the Air Force. This is not an easy task. The RMLV designers will have to fully understand the reasons for the performance limitations of the other space launch systems and avoid design decisions that have limited their responsiveness, while maintaining a reliable system that builds on current technologies.

The research presented in this paper is part of an effort to help inform the RMLV designers as to the implications of various vehicle design decisions through the application of a discrete-event computer simulation model for the RMLV post-landing

recovery operations, in the context of Air Force doctrine and goals of a highly reliable and responsive spacelift capability.

Problem

The primary challenge the Air Force faces regarding the RMLV is responsiveness. RMLV regeneration time must be short enough to provide that responsiveness. The regeneration process consists of three basic phases: post-landing vehicle recovery, maintenance, and prelaunch operations. The first of these three phases includes actions to make the vehicle safe for ground crews to operate near the vehicle, safety assessments to detect hazardous conditions, actions to protect the vehicle during movements, and actions to make the vehicle safe to put into the maintenance facility. This phase is the shortest of the three phases of vehicle regeneration, but is critical to ensuring safe and timely maintenance can be performed on the RMLV to prepare it for its next mission. Capt Ty Pope addressed the vehicle maintenance portion of the RMLV regeneration process in his thesis from the Air Force Institute of Technology, and Capt Adam Stiegelmeier addressed RMLV prelaunch operations in his thesis from the same institution (Pope, 2006/Stiegelmeier, 2006). The models that resulted from their research were comvined into onne model call MILePOST. The model product from this research will e added to MILePOST to offer a complete regeneration model for AFRL/VA researchers. With respect to time, the post-landing vehicle recovery process is much shorter and less complex than the other phases, but is equally impacted by major vehicle and system design decisions that will determine whether the Air Force can reach its regeneration performance goals for the RMLV.

Research Objective

The purpose of this research is to aid the Air Force in the effort to determine the most effective post-landing vehicle recovery process based on vehicle and system design decisions by creating a discrete-event simulation model of a generic RMLV post-landing vehicle recovery process. This model can help decision makers evaluate vehicle and system design tradeoffs to develop the most effective RMLV system to support Air Force's spacelift requirements. It can also identify portions of the vehicle recovery process that are the most sensitive, with regard to time, to design decisions. To guide the research, the following research question is proposed:

> *How can the Air Force develop a discrete-event computer simulation model of RMLV post-landing vehicle recovery operations that will aid decision makers in evaluating RMLV and system design alternatives?*

The research question is divided into the following investigative questions:

1. What generic functions, or sequence of actions, describe RMLV post-landing vehicle recovery operations?
2. How do these RMLV post-landing vehicle recovery operations functions compare to space shuttle orbiter and aircraft post-landing recovery operations?
3. What are the RMLV design drivers that will influence RMLV post-landing vehicle recovery operations, and how will these affect the number, type, and duration of RMLV post-landing vehicle recovery operations activities?
4. How can these RMLV design drivers and post-landing vehicle recovery operations activities be incorporated into a discrete-event simulation model

that captures a baseline RMLV post-landing vehicle recovery operations sequence?

5. What RMLV regeneration timeline insights can be gained from running the model using notional but plausible inputs?

Summary and Preview

This chapter provided a general overview of the doctrinally driven need for a responsive and timely spacelift capability within the Air Force. The purpose for the research was identified with a research overview in the form of a research question and investigative questions. Chapter II will provide an overview of the Air Force's future goals for spacelift in the context of national policy, general post-landing vehicle recovery processes from the Space Shuttle orbiter and the F-16 fighter aircraft, and s comparison of the attributes of both processes. Chapter III will describe the methodology used in this research. Chapter IV will include a description of the model developed for this research, as well as the model verification and validation processes and their results. Chapter V will offer research conclusions and recommendations for future research to expand and improve upon this research.

II. Literature Review

Introduction

This chapter will provide the background used for developing the RMLV post-landing vehicle recovery discrete-event computer simulation model. The background for understanding how this research fits within the broader context is provided in three parts. First, understanding the Air Force's future spacelift objectives will place the RMLV and the importance of designing the optimum system and processes into the appropriate context. Second, the post-landing vehicle recovery processes for the F-16 and Space Shuttle orbiter and F-16 fighter aircraft provide the basis for the model's construct, so these processes are summarized in this chapter. Third, the orbiter and F-16 processes are compared to highlight design and process differences that impact the design and process decisions for the RMLV.

Future Air Force Spacelift Objectives

The Air Force's goals regarding spacelift can be viewed in the context of U. S. Space Transportation policy, and are articulated through the concept called Operationally Responsive Space (ORS). The primary goal of US Space Transportation policy is "to ensure the capability to acess and use space in support of national and homeland security, civil, scientific, and economic interests" (US Space Transportation Policy, 2005:2). The first two objectives supporting this goal are as follows:

> 1. “Ensure the availability of U.S. space transportation capabilities necessary to provide reliable and affordable space access, including access to, transportation through, and return from space;
>
> 2. Demonstrate an initial capability for operationally responsive access to and use of space – providing capacity to respond to unexpected loss or degradation of selected capabilities, and/or to provide timely availability of tailored or new capabilities – to support national security requirements” (US Space Transportation Policy, 2005:2)

The Air Force is leading the joint Department of Defense (DoD) effort to investigate ORS technologies (Cebrowski and Raymond, 2005:77). In the broadest terms, the Air Force’s goal is to provide space capabilities in “hours to days” with the ORS concept, rather than the “weeks to months” capability that exists in current launch systems and processes (Stewart, 2003). The concept for ORS that Air Force Space Command (AFSPC) is developing consists of three elements: a reusable first-stage booster, an expendable second-stage vehicle, and responsive payloads (Brown, 2004:3). The first element is where the RMLV concept supports ORS development.

Space Shuttle Orbiter Recovery Processes

The Space Shuttle Orbiter post-landing recovery team consists of approximately 150 trained personnel to assist the flight crew in leaving the orbiter, make the orbiter safe for towing and maintenance, prepare for towing, and tow the orbiter to the Orbiter Processing Facility (OPF) (NASA Facts, 2000:7). The team uses about 25 vehicles of various size and purpose to carry the variety of ground support equipment (GSE) required

to service the orbiter (NASA Facts, 2000:7). The primary GSE that warrant discussion for the purposes of this research are the Purge Vehicle, Cooling Vehicle, the Purge and Cooling Umbilical Access Vehicles, the fan trailer, and the hand-held hazardous gas detectors. The Purge Vehicle (Figure 2.1), operated by the Purge, Vent and Drain (PVD) engineering group, provides cooled and conditioned air through purge ducts with tributaries to the forward, mid-body, and aft cavities of the orbiter where there is potential for hazardous gases to accumulate, to include the hydrogen and LOX ducts that feed the Space Shuttle Main Engines from the External Tank (Wood/Tour).

Figure 2.1 Purge Vehicle, Kennedy Space Center

The Cooling Vehicle (Figure 2.2), operated by the Environmental Control Systems (ECS) engineering group, pumps chilled Freon R124 refrigerant into a piping system that

interacts with the orbiter's cooling system via an on-board heat exchanger to maintain temperatures of electronics systems black boxes and controls (Wood/Tour).

Figure 2.2 Cooling Vehicle, Kennedy Space Center

The Purge and Cooling Umbilical Access vehicles (Figure 2.3) provide the PVD and ECS crews with access to the rear areas of the orbiter to connect the purge and cooling umbilicals (Wood/Tour).

Figure 2.3 Purge Umbilical Access Vehicle, Kennedy Space Center

The fan trailer (Figure 2.4) is a large fan, similar to agricultural fans, used to create an air current over the orbiter to redirect hazardous away gases from the crew compartment so that crew recovery operations can continue. Wind direction and speed will determine the use of the fan machine and its positioning near the orbiter's nose section (Wood/Tour).

Figure 2.4 Fan Trailer

The hand-held hazardous gas detectors are used by ground safety assessment teams to test and monitor the area around the orbiter for the presence of dangerous levels of hazardous gases emanating from the orbiter. The team uses a variety of detectors, and also wears dosimeter cards to monitor their exposure to the hazardous gases (Wood/Tour). The ground support equipment (GSE) above, together with the equipment required to recover the flight crew, are required to recover the orbiter, but only those mentioned above apply directly to the RMLV post-landing recovery model (NASA Facts, 2000:7). To understand the purpose of the various vehicles is not enough, the macro-level processes must be understood as well to accurately apply them to the RMLV model.

After the orbiter stops on the runway, the recovery convoy moves to a position 1250-feet from the orbiter. The safety assessment teams move forward ahead of the convoy in protective suits and breathing apparatus to take vapor level readings and test

for explosive and toxic gases that may be present. Hazardous gases that pose a threat to the flight and recovery crews are hydrogen, hydrazine, monomethyl-hydrazine, nitrogen tetroxide or ammonia (NASA Facts, 2000:7). If the assessment team detects hazardous gases, the convoy is withheld until the fan trailer is in place and can create sufficient airflow to redirect the hazardous gases so that recovery operations can continue (Wood/Tour).

Following the fore and aft safety assessments, the Purge and Coolant Umbilical Access Vehicles are positioned behind the orbiter to gain access to their respective umbilical areas. At this time the ground portion of the on-board hydrogen detection system are connected to the orbiter to determine the hydrogen concentration. If there is no threat to the flight and ground crews, recovery operations continue. If hydrogen is detected, the flight crew is evacuated immediately, and the ground crews are moved to a safe distance until an emergency power-down of the orbiter is complete and the hazardous condition is eliminated (NASA Facts, 2000:7-8).

Once the hydrogen and oxygen umbilical lines are connected from the Purge Umbilical Access Vehicle, cool and conditioned air is used to purge the payload bay and other cavities on the orbiter to remove residual or toxic fumes that may threaten the flight or ground crews. The purge normally occurs within 45-60 minutes after the orbiter stops on the runway. At the same time, the Coolant Umbilical Access Vehicle is connected to the orbiter and takes over cooling functions from the orbiter’s on-board cooling system, allowing it to be shutdown (NASA Facts, 2000:8). The photograph in Figure 2.5 shows the Purge and Cooling umbilical access vehicles in place and the ground crew connecting the umbilicals to the orbiter.

Dryden Flight Research Center EC90 129-6 Photographed 4/90
Shuttle recovery team in action following landing of STS-31 on Dryden runway 22.
NASA photo.

Figure 2.5 Purge and Cooling Vehicles Connected to Space Shuttle Orbiter

When the area in and around the orbiter is safe, the Crew Hatch Access Vehicle moves to the hatch side of the orbiter and is mated to the hatch. The flight crew egresses the orbiter after a preliminary medical examination, usually within an hour of landing. Exiting through the "white room" attached to the Crew Hatch Access Vehicle to the Crew Transport Vehicle, the flight crew departs the orbiter after the commander, and occasionally other crew members, performs a walk around the orbiter (NASA Facts, 2000:8).

After the crew exits the orbiter and the ground cooling is initiated, Johnson Space Center (JSC) transfers orbiter control to Kennedy Space Center (KSC). At this point the

exchange support personnel enter the orbiter to prepare it for towing operations by installing switch guards and removing data packages from on-board experiments (NASA Facts, 2000:8).

A total safety downgrade decision is made, enabling the ground crew to continue with tow preparations. The final tow preparations include installing landing gear lock pins, positioning the tow vehicle, and connecting the tow bar. Tow typically begins within four hours of landing and is complete within six hours of landing (NASA Facts, 2000:8). It is important to note, as seen in Figure 2.6 which shows the orbiter nearing the end of the towing process, that during towing operations the Purge and Cooling vehicle are both connected to the orbiter and operating during the entire towing operation (Tour).

Figure 2.6 Towing Orbiter with Purge and Cooling Vehicles Connected

During the post-landing recovery operation, an engineering test team monitors data from orbiter systems from one of the Launch Control Center’s firing rooms. Once orbiter control is handed over to KSC, this engineering team can issue commands to the orbiter to configure specific orbiter systems for towing to the OPF (NASA Facts, 2000:8).

Fighter Aircraft Recovery Processes

The post-landing recovery process for the F-16 fighter aircraft requires some minor pieces of GSE, and typically only four personnel (Kirk). The GSE required includes an oil servicing unit, aircraft boarding ladder, fire extinguisher, various ground lock and safety pins, and aircraft grounding and communications equipment (T.O. 1F-16CG-6WC-1-11:4-004).

The process begins when the pilot taxies the aircraft to the recovery apron. The ground crew first inspects the aircraft for indications of the hydrazine powered emergency power unit (EPU) having been used during the flight and for hydrazine leaks. If there are indications that the EPU was used, the ground crew must confirm with the pilot that it was used during the flight and is no longer running. If the EPU is running, or there are indications of a hydrazine leak, local base emergency procedures dictate the ground crew's actions. If all indications are normal, the ground crew proceeds with aircraft recovery (T.O. 1F-16CG-6WC-1-11:4-007).

The ground crew then installs and verifies safety pins are installed in the weapons and external fuel tank pylons, missile launchers, gun firing circuit, and the chaff-flare dispenser (T.O. 1F-16CG-6WC-1-11:4-008). The pylon and missile launcher safety pins are installed to prevent inadvertent firing of the pyrotechnics used to separate the pylon from the aircraft in-flight. The gun firing circuit safety pin prevents inadvertent firing of the gun on the aircraft. The chaff-flare safety pin prevents the accidental dispensing of chaff and flares. All of these actions protect the ground crew and other personnel that may be in the area.

Following the safety pin installation, the aircraft is parked. During this process the ground crew inspects for hot brakes, a condition that could result in a life-threatening tire blowout. Once the aircraft is in position, chocks are installed to prevent rolling and the ground crew inspects the aircraft tires. Finally, the ground crew installs the cord on the headset/microphone and establishes communication with the aircrew (T.O. 1F-16CG-6WC-1-11:4-009 – 4-011).

The communication link allows the ground crew to confirm with the aircrew the condition of the EPU prior to installing the EPU ground safety pin. The EPU ground safety pin prevents the firing of the EPU and the hazardous condition that would result from exposure to hydrazine and exhaust from the EPU (T.O. 1F-16CG-6WC-1-11:4-012).

The final portion of the post-landing recovery process involves inspecting for various fluid leaks from the aircraft prior to the pilot taxiing the aircraft to the maintenance area to turn the aircraft over to maintenance crews to service the aircraft (T.O. 1F-16CG-6WC-1-11:4-013 – 4-014).

The entire post-landing recovery process for the F-16 typically takes 3-4 minutes from start to finish. Many processes, such as installation of ground safety pins, are performed in parallel. Also, based on the number of times the operation has run since the introduction of the F-16 in the mid-1970’s, the process is as refined as possible.

Comparing Space Shuttle Orbiter and F-16 Post-Landing Recovery Processes

Comparing the Space Shuttle Orbiter and F-16 post-landing recovery operations reveals some useful lessons for the proposed RMLV. The two operations share some of

the simpler processes, but what is of greatest interest are the processes which share the same purpose, but the complexity of the processes based on the vehicle system design are dramatically different. The result is significantly longer process times for the orbiter. In addition to process complexity, the orbiter also requires activities not performed on the F-16 based on its system design.

The orbiter and F-16 share the common processes of requiring ground safety pins and ground lock pins to be installed in various portions of the vehicle, such as the landing gear and pyrotechnics. Most of these simpler processes are so similar for the two vehicles, they can be considered the same in both function and approximate duration. These are also the processes that are likely to be required no matter what the design of the RMLV.

The orbiter and F-16 also share processes that have a common purpose, such as protect the ground and flight crew from hazardous gases associated with the hydrazine powered APU on the orbiter and the hydrazine powered EPU on the F-16, but the actual processes used vary in complexity and length. The process for the orbiter requires several personnel with hand-held sensors to take readings close to the orbiter to determine whether a hazardous condition exists, with no other activities occurring until the area is deemed safe for flight and ground crews. The F-16 process involves a visual check of the EPU firing indicator and a visual inspection for leaks, and a follow-up confirmation that the flight crew has no indications of a hazardous condition. The orbiter process takes, on average, 12-minutes for the fore and aft assessments, performed concurrently (see Attachment 2). The F-16 process takes less than five minutes (Koehler). Clearly, the two processes are substantially different, the advantage going to

the F-16 process for having on-board indications, given to the maintenance crew in the form of a warning flag on the external surface of the aircraft and communication from the pilot, instead of external sensors to reduce the time required to conduct the safety assessment.

The Space Shuttle Orbiter is subject to four processes during post-landing recovery that are not performed on the F-16 aircraft. The first is the purge process, the functions of which are performed by the purge equipment on the Purge Vehicle described earlier in this chapter. The second process is ground cooling which requires the Cooling Vehicle, also described earlier in this chapter. The third process is the removal of the flight crew on the runway. In the F-16 process, the flight crew does not leave the aircraft until it reaches the maintenance area while the orbiter crew exits the vehicle on the runway as a part of the post-landing recovery process. The fourth is the movement from the recovery area to the maintenance facility. As discussed earlier, the orbiter travels in a convoy from the runway to the OPF, towed by a tug, and with the Purge and Cooling vehicles following with their respective umbilicals connected to the orbiter. The process and coordination required to tow the orbiter to the OPF is far more complex and time consuming than the process to taxi the F-16 from the recovery area to the maintenance area.

Summary

This chapter provided the necessary background in the future Air Force spacelift objectives, and the Space Shuttle orbiter and F-16 post-landing recovery processes, and provides a comparison of the Space Shuttle and F-16 processes. Future Air Force spaclift

objective address the requirement for responsive space lift with the capabilities to respond to spacelift requests in hours to days instead of the weeks to months required with current systems. The orbiter and F-16 processes were used as the basis for the RMLV process model, with an emphasis on orbiter processes due to the unique nature of space systems and the need to address the maximum number of possible design issues. Finally, the comparison of the F-16 and orbiter processes demonstrates the need to not simply copy the Space Shuttle Orbiter in designing the RMLV if the Air Force is to meet its performance goals. Next, Chapter III will discuss the methodology used to develop, verify, and validate the RMLV post-landing recovery model.

III. Methodology

Introduction

This chapter explains the methodology used to develop the RMLV post-landing vehicle recovery operations simulation model. The first section will explain the advantages of using discrete-event simulation modeling for the problem of RMLV post-landing vehicle recovery operations. The second section will explain the 12-step modeling process used to build the model.

Advantages of Using Discrete-Event Simulation Modeling

Discrete-event simulation modeling, in general, is an excellent tool for evaluating new or changing systems. In relation to the RMLV, discrete-event simulation is an appropriate tool for assisting in designing new systems. The simulation can allow the designers to experiment with internal interactions of complex systems, such as the RMLV. It can also provide valuable insight into which variables are most important to process interactions. The most important advantage of simulation for the RMLV design process is the ability to evaluate various designs without committing resources to building the actual hardware (Banks and others, 2005:4-6).

The 12-Step Modeling Process

The 12-Step modeling process described by Banks et al. is designed to guide model development for a broad range of applications (Banks and others, 2005:15). The first seven steps of the process guide model development, while the last five steps guide

the use or application of the model to analyze and make decisions about the system modeled. The following identifies each of the twelve steps of the modeling process and explains the actions taken to design the RMLV post-landing vehicle recovery model.

Step 1: Problem Formulation

The research problem is the heart of the entire modeling effort, all work is centered on and guided by the need to solve the research problem (Banks and others, 2005:14). The Air Force Research Laboratory, Air Vehicles Directorate (AFRL/VA) is in the early stages of RMLV development and requires a discrete event simulation model of the RMLV post-landing recovery process to assess the impact of various vehicle and system design options that can work in conjunction with the MILePOST model developed by Pope and Stiegelmeier.

Step 2: Setting of Objectives and Overall Project Plan

Once the research problem is made clear, the researcher must determine the objectives of the research effort, usually stated in the form of research questions, and design a project plan to achieve those objectives (Banks and others, 2005:14). The primary objective of this research is to provide AFRL/VA with an effective model for analyzing design alternatives for the RMLV based on post-landing vehicle recovery operations. The general plan for accomplishing that objective was to apply this 12-Step Modeling Process within an approximately five month timeline. The problem, research objective, research question, and investigative questions were identified in Chapter I.

Step 3: Model Conceptualization

Model conceptualization is essentially the visualization and initial brainstorming work required to begin building the framework for the model (Banks and others,

2005:14). The author began with broad concepts of aircraft and Space Shuttle orbiter post-landing recovery operations, separating the processes into the three broad categories:

1. *Making the vehicle safe for ground crews* – Actions required to protect ground crews from potential hazards on or near the vehicle due to the nature of the vehicle design.

2. *Protecting the vehicle from damage* – Actions required to protect the vehicle from damage during handling and from the local environment.

3. *Preparing the vehicle for transportation and maintenance* – Actions required to prepare the vehicle for transportation and make it safe and ready to enter into the maintenance process.

Once identified, the three broad categories were used to guide research into both the F-16 and Space Shuttle orbiter post-landing recovery operations. The research outlined in Chapter II revealed specific actions taken that could be applied to the more generic model for the RMLV.

Step 4: Data Collection

Data collection requirements are based on the research objectives, but typically this step involves collecting and analyzing historical performance data for the system being modeled (Banks and others, 2005:16). The Space Shuttle orbiter post-landing recovery performance data was used as the primary source for data analysis with the F-16 data secondary. In initial analysis of the data, probability distributions were fit to the data for some of the key processes from the Space Shuttle orbiter post-landing recovery to determine some core statistics such as the mean and standard deviation for the data. This information was used in initial modeling runs, but was later altered to meet AFRL/VA requirements for triangular distributions with lower bounds set at 10% less than the mean and upper bounds set at 40% above the mean. For many of the processes in the model there was no historical data available for analysis, but the mean for the processes were

available for either the Space Shuttle orbiter or the F-16. In general terms, the Space Shuttle orbiter data was used for the majority of the RMLV post-landing recovery processes. The F-16 data was primarily used for processes involving the handling of external stores in the instance of a contingency where the payload does not successfully separate from the RMLV.

Space Shuttle Orbiter data came in two forms. The first is a timeline of all processes conducted during Space Shuttle landing runway operations. The timelines for each process are based on historical averages for that process, however the supporting data is not available to conduct input analysis to determine appropriate distributions and variances (see Attachment 2). The second data source is a spreadsheet with data on processing times for eight key processes from the fifty-eight Space Shuttle missions from 1991 to 2002. The input analyzer function of the Arena 7.01 software was used to conduct input analysis on the data for these eight key processes. Input analysis involved evaluating the data to determine the form of the statistical distribution of the data. The results of the input analysis are contained in Table 3.1.

Process	**Mean**	**Standard Deviation**	**Distribution**	**Chi^2 Test P – Value**	**Square Error**
Reaction Jet Drives / Hatch Safing	6.88	1.98	Normal	0.212	0.013184
Forward Downgrade	12	2.29	Gamma	0.0957	0.021840
Aft Downgrade	12.8	2.8	Weibull	0.433	0.008259
APU Shutdown	18.3	2.68	Erlang	0.519	0.009864
Left Hand Upper Inspection	27.1	4.06	Lognormal	0.445	0.008601
Right Hand Upper Inspection	27.7	4.99	Gamma	0.132	0.017209
Purge Initiated	53.7	9.62	Poisson	0.0226	0.025838
Cooling Initiated	48.6	9.61	Triangular	0.471	0.022401

Table 3.1. Input Analysis Results for Eight Key Processes

The Arena input analyzer selects the best distribution based on the square error (Arena). The square error is a measure of the sample variability around the fitted distribution line, with the lowest variability providing the best fit. The second criterion for goodness of fit is the P-Value from the Chi^2 Test, which is desired to be the highest for the best distribution fit (Arena). In considering the P-Value results from the output analysis, the APU Shutdown, Upper Left Hand Inspection, and Cooling Initiated processes have strong values. All others are not as significant and allow for more flexibility in choosing another distribution, if desired. After initial analysis, all distributions were made triangular according to AFRL/VA requirements. While providing an evaluation of the system dynamics under different RMLV designs, the RMLV post-landing model also is victim of one of the disadvantages of modeling and simulation, limited or incomplete data (Carson, 2005:18). Essentially, there is no complete data set for all the processes in the RMLV post-landing system.

The F-16 data came in the form of average process time for the complete post-landing recovery process, provided by the Second Lieutenant Abby Keohler, an F-16 maintenance officer. Individual process data for the F-16 was not available for this study. Additional information came from the personal insight and experience of Major Timothy Kirk, a former F-16 maintenance officer.

Step 5: Model Translation

The conceptual model developed in Step 3 must be translated into a computer modeling software package in order to study the representation of the real world system (Banks and others, 2005:16). The RMLV post-landing vehicle recovery operations model was built in Arena computer simulation software according to AFRL/VA

requirements. The primary challenge in translating the conceptual model into a computer simulation model is in ensuring the conceptual processes are accurately represented in the model according to how the software handles the data. Step 6 addresses this challenge.

Step 6: Verification

Model verification is the process used to confirm the model works correctly as it is designed. Verification will often include debugging of the software and testing the model to ensure it behaves properly according to the modeler's intent (Banks and others, 2005:16). The process can include stress tests on the model using different random numbers, a review of model outputs, software debugging, selective traces throughout the model, and review by more senior simulation analysts (Carson, 2005:21). Of these possible methods, this researcher used the Arena software debugger to identify problems in the model logic, a review of model outputs against expected results, and selective traces through the assertion checking process.

During initial simulation runs the Arena software debugger identified errors in logic regarding resources that were referenced but not defined in the system. These problems were easily resolved because the referenced resources were residual from early versions of the model and were no longer required.

Output analysis identified a major problem in the model. In early runs, the model accurately entered one entity into the system, but three to four entities would exit the system causing errant output data. The problem was found in two of the separator modules used to model parallel processes, which were set to produce four duplicates instead of the needed one duplicate. The result was the batching module created entities with the additional duplicates according to their programmed logic. This problem was

easily resolved, and subsequent simulation runs produced the expected one entity per replication.

The assertion checking method was used to test the model to ensure it performs as expected based on known inputs. The assertions are made in the model in the form of dictating the decisions made for the decision modules, and then the model is run and the output results compared to the expected results to determine whether the model performs correctly (DoD VV&A, 1996:4-13). For this model, the design decisions made using the rudimentary user interface were the assertions and the use, or lack of use, for the resources assigned to each process that would be used based on the decision were the markers to indicate whether the decision module performed correctly based on the input from the user interface.

Step 7: Validation

Validation is the process of ensuring the model accurately portrays the system it is intended to model. Validation is an iterative process in which the simulation's behavior is compared to the behavior of the real world system to ensure the real world system's behavior is accurately represented in the model (Banks and others, 2005:16). Many methods are available to validate a model, but two primary methods were used in this model. First, the Delphi process was applied to gain the advantage of having experts from the fields of Space Shuttle orbiter and F-16 post-landing vehicle recovery operations review the construct of the model to ensure all of the necessary processes are captured in the model, as well as all potential design options (Delphi). The Delphi process was particularly useful in the development of this model because a reusable, unmanned first-stage launch vehicle does not currently exist. Lacking direct data or knowledge of how

design decisions would affect the performance of the RMLV, drawing on the knowledge of experts from different areas allows the modeler to determine system performance with a good degree of certainty in the absence of data. MacMillan and Marshall used this approach in constructing models to determine the impact of environmental factors on endangered species when the scientific data supporting a decision guiding model was missing or inadequate. MacMillan and Marshall found that the application of the Delphi process to model construction was useful and effective in developing working models to help guide forestry decisions to assist in the recovery of the endangered populations when complete data is not available (MacMillan and Marshall, 2005:11,18).

Second, the model output was analyzed to assess its reasonableness when compared to the data it was built upon. Individual processes were not assessed for their reasonableness. The overall process output, the time to completion was compared against the Space Shuttle Orbiter process times to determine the reasonableness of the model as constructed with favorable results.

Step 8: Experimental Design

In the experimental design step, the modeler designs a framework for experimentation to evaluate the alternative designs for the system modeled (Banks and others, 2005:16-17). The author conducted preliminary experiments to test the vehicle and system design alternatives that are available in the model using the Space Shuttle orbiter and F-16 derived distributions. The purpose of these experiments was to assist in model validation and verification.

Step 9: Production Runs and Analysis

Production runs are required to produce the data required to analyze the alternative designs in the system (Banks and others, 2005:17). The preliminary production runs were used to help verify and validate the model for this research. The production runs to evaluate the design alternatives will be performed by AFRL/VA researchers. However, these production runs will be run on the consolidated MILePOST regeneration model.

Step 10: More Runs?

The purpose of this step is to determine whether more experimentation is required to achieve the purposes of the analysis (Banks and others, 2005:17). More experiment runs may be required to improve the statistical significance of the results, or the experiment may need to be altered to better test the alternatives the customer is interested in. In the case of this model, AFRL/VA will conduct any further experiments with the model.

Step 11: Documentation and Reporting

Documentation can take two forms, program and progress. Program documentation is designed to communicate how the computer program works for later users (Banks and others, 2005:17). The Arena computer modeling software used in this research is well documented as a commercial product and requires no further documentation. Progress documentation and reporting records and communicates the history and success of the modeling project (Banks and others, 2005:17). Progress reporting for this research is satisfied in the text of this document, however, AFRL/VA

will have additional progress reporting requirements to report the results of the production and analysis phase of the completed modeling project.

Step 12: Implementation

Implementation is the use of the information and insight gained from the simulation model to help guide decisions in the design of the real-world system (Banks and others, 2005:17-18). The purpose of this research is not to implement decisions, but rather to equip AFRL/VA with a simulation model to conduct their own analysis of potential RMLV designs and implement the results at some future date. This research will not make or implement any decisions resulting from the use of this model.

Summary

Chapter III described the advantages of using discrete-event simulation and the process used to develop the RMLV post-landing vehicle recovery operations computer simulation model. The 12-Step process from Banks et. al. provided the framework for the development of the problem, objectives, the model, verification and validation, and progress reporting. The remainder of the 12-Step process is incumbent of AFRL/VA to complete to ensure accurate production runs, continued reporting, and implementation of the design insights gained from the use of the RMLV post-landing recovery operations computer simulation model.

IV. Results and Analysis

Introduction

This chapter describes the model created for this research and presents the results of the model verification and validation processes explained in Chapter III.

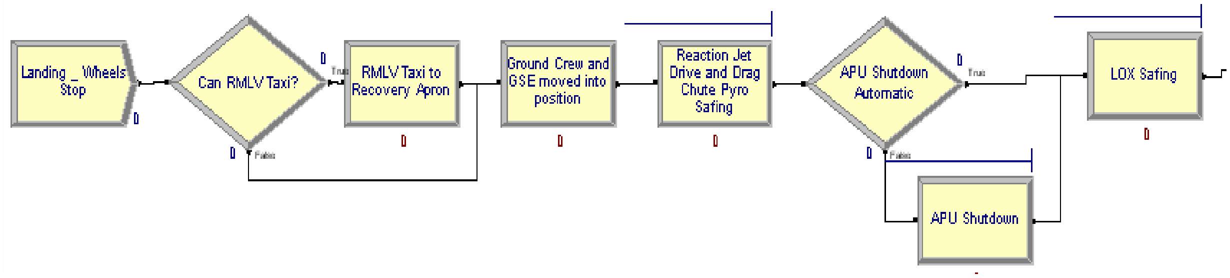
Model Description

The Arena computer simulation modeling software was used to develop this model. A rudimentary user interface was developed in Microsoft Excel software to allow the user to change the distributions used for each process and direct entity behavior in the decision modules. The entire RMLV post-landing vehicle recovery operation can be broken down into seven segments:

1. Landing, taxi (if capable), and initial safing
2. Safety assessment and final safety call
3. RMLV preparation for transportation
4. Handling external stores (if required)
5. Safing sequence
6. Tow preparation
7. Towing to the maintenance facility

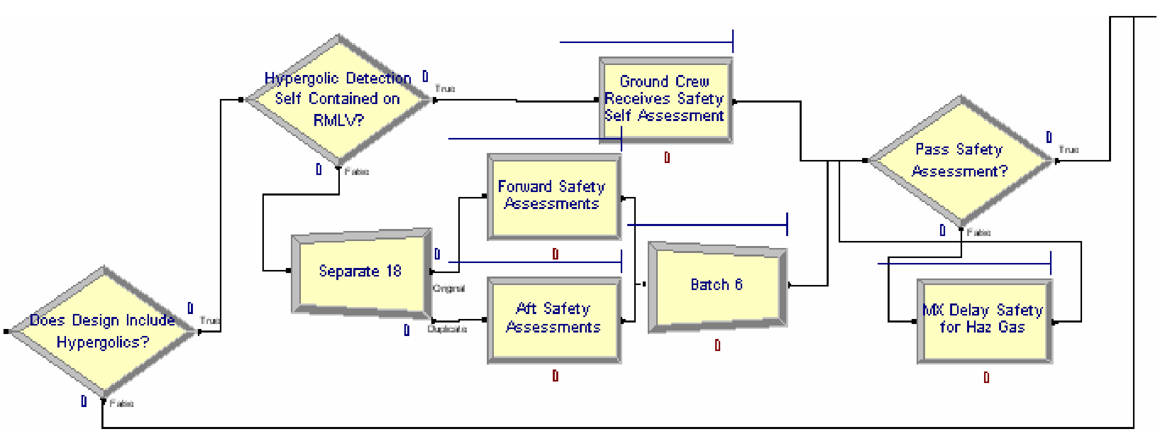
Some of these segments occur in parallel, such as the safing sequence and tow preparation. Segment 3 is non-contiguous and occurs in two small segments separated by Segment 4. Each segment involves several individual processes required to safely recover the vehicle and transport it to the maintenance facility.

Segement 1: Landing, Taxi, and Initial Safing



The first segment of the model includes the process modules that represent the activities required to safe portions of the RMLV which pose a threat to the ground crew. The first decision module provides the option to make the RMLV capable of taxiing. The first process is for the RMLV to taxi off the runway to the recovery apron, if capable. The second process represents the safing of the reaction jet drives and drag chute pyrotechnics. The next module is a decision module that allows the designers to evaluate the advantages and disadvantages of have the RMLV capable of automatic auxiliary power unit (APU) shutdown. If the RMLV is capable, the entity in the model will proceed directly to the next process, if not, the entity will enter the process for ground crew shutdown of the APU. The final process represents the ground crew safing of the LOX tank to ensure no venting occurs which could produce a fire hazard condition.

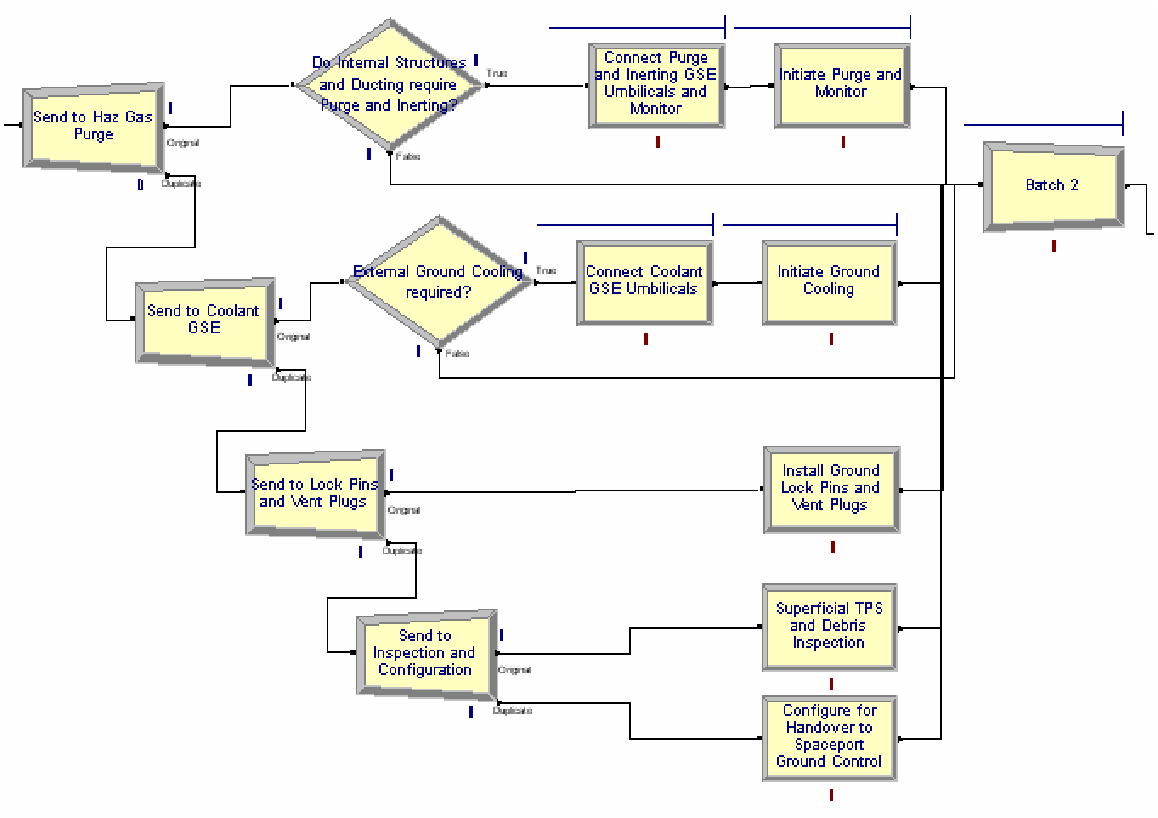
Segment 2: Safety Assessment and Final Safety Call



This segment is broken down into two portions, the first being the initial safety assessment required to determine if it is safe for the ground crews to continue maintenance on the RMLV, and the second being the final safety call to allow complete recovery processing and transportation to the maintenance.

The first module is a decision module which allows designers to evaluate the impact of having hypergolic fuels on the RMLV. If the RMLV does not include hypergolic fuels, the entity in the model by-passes Segment 2 of the model and continues into Segment 3. If it does include hypergolic fuels, the designer has the option to make the safety assessment regarding hazardous gases associated with hypergolic fuels automated within the RMLV, or to require ground support equipment sensors operated by the ground crews to conduct the safety assessment. If the safety assessment is automated, the entity proceeds to the decision module representing the outcome of the assessment. If the ground crew must conduct the safety assessment, the entity enters the parallel process modules representing both the forward and aft safety assessments before proceeding to the decision module. The final process in this segment represents maintenance actions required to make conditions safe around the RMLV should the safety assessment team detect hazardous gases. This process is analogous to the requirement to use the fan trailer on the Space Shuttle orbiter recovery.

Segment 3 (Part 1): RMLV Preparation for Transportation

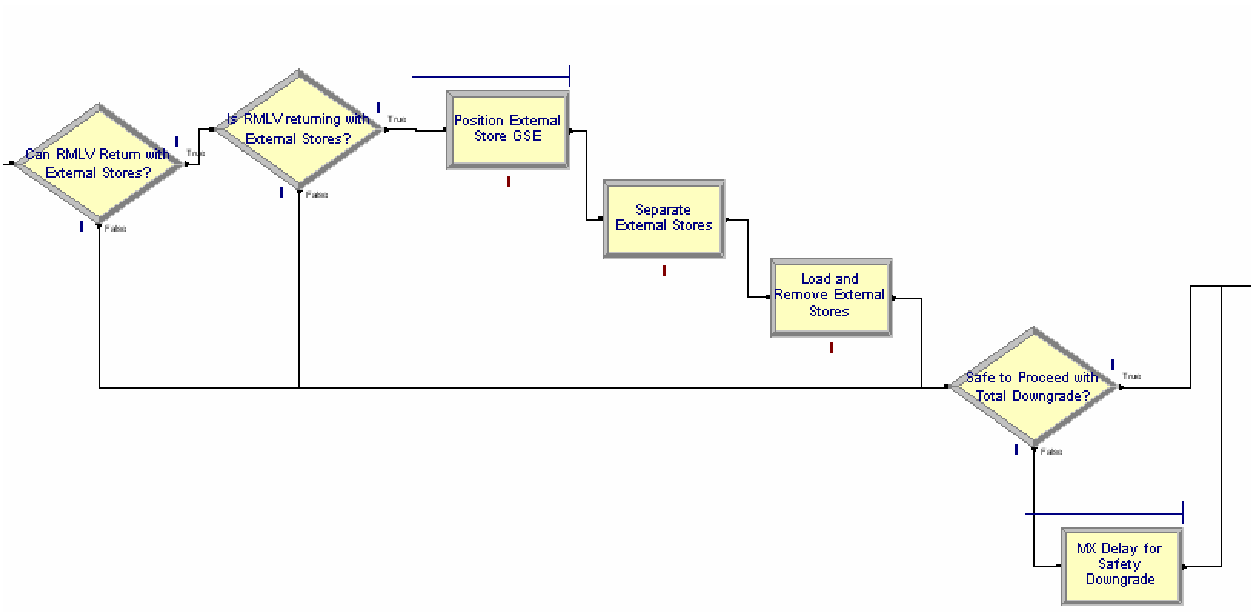


Segment 3 is represented in two portions of the model. The first portion includes actions that, if required, should be addressed before any other actions are taken in order to protect the RMLV and make it ready to enter the maintenance facility as quickly as possible. The second portion includes what may be considered less critical actions which are still required prior to towing operations.

The first portion of Segment 3 includes several parallel processes. The first involves the decision to design a RMLV requiring purging due to the potential presence hazardous gases. The ground crew must connect GSE to conduct a hazardous gas purge, initiate the purge, and monitor for any leaks. If the RMLV design does not include the requirement to purge hazardous gases, the decision module bypasses these processes. The second of the parallel processes represents the design decision for a RMLV that

requires external cooling to protect on-board components. If cooling is required, the ground crews must connect GSE and conduct cooling operations to protect the internal RMLV components. If cooling is not required, the entity bypasses the cooling processes. The final three parallel processes represent ground crew actions required to install landing gear lock pins and protective covers on surface vents. Ground crews conduct a superficial inspection for damage to the RMLV thermal protection system (TPS) and for debris that could further damage the RMLV or pose a hazard to ground crews and equipment should the RMLV be moved, and any additional RMLV configuration actions required before turning over control of the RMLV.

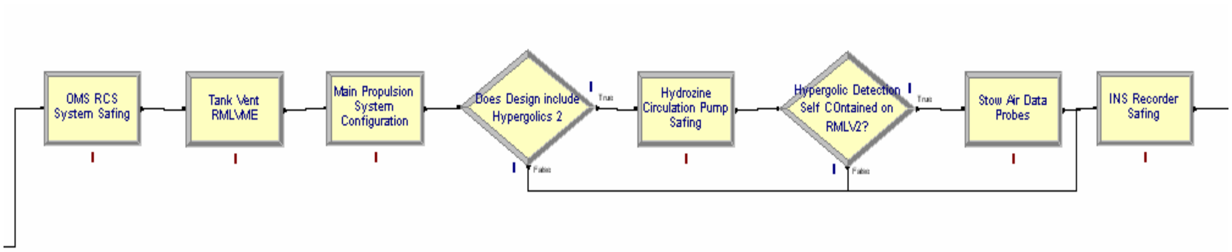
Segment 4: Handling External Stores



This segment of the operation allows the designers to decide if the RMLV should be capable of returning with external stores. If the RMLV can return with external stores, designers can choose to evaluate the impact of this contingency. The three process modules represent the positioning of GSE, the separation of the external stores from the RMLV, and the removal of the external stores from the area. Following the removal of

the external stores the entity proceeds to the decision module for safety downgrade where, if passed, it will continue with recovery operations. If the safety downgrade fails, the entity is sent to a process module that represents the additional maintenance required to correct the problem causing the failure, then continues with recovery operations.

Segment 5: Safing Sequence

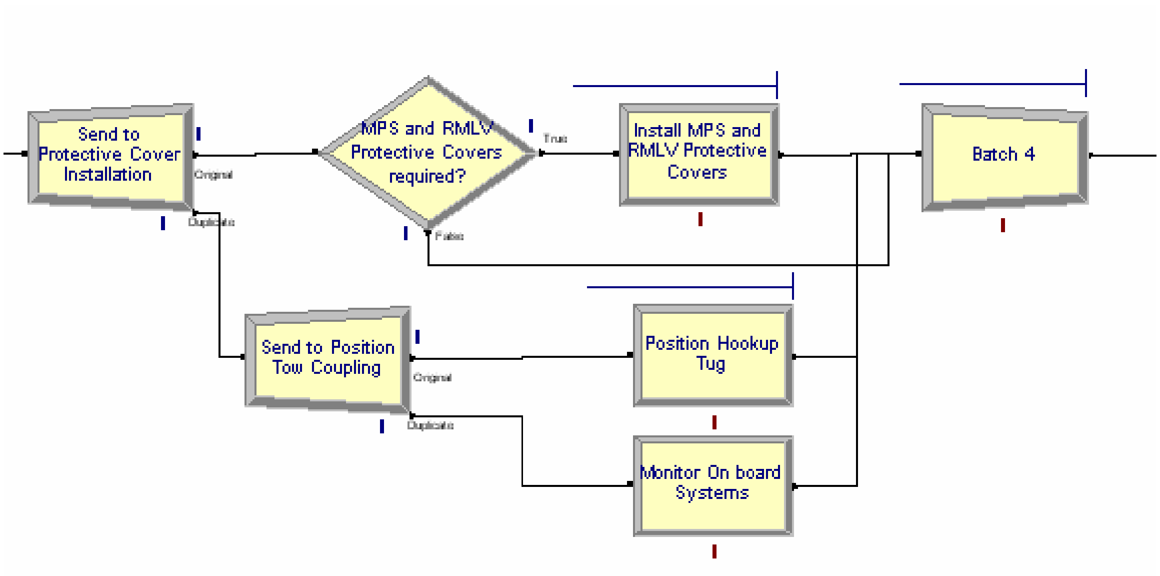


The safing sequence includes several activities that are expected to be required regardless of RMLV design, and a few that will only be required if the design includes the use of hypergolic fuels. The first process represents the safing of the orbital maneuvering system (OMS) reaction control system (RCS) to ensure the RCS does not inadvertently fire and harm ground personnel or damage the maintenance facility and RMLV. The second process represents the venting of fuels and fumes from the RMLV main engine (ME) tanks to ensure potential hazards are eliminated prior to the vehicle entering the maintenance facility. The third process represents the configuration for the main propulsion system (MPS) to prepare it to enter the maintenance facility.

The decision module following the third process allows the designers to evaluate the impact of using hypergolic fuels. If included, the entity proceeds to the hydrazine circulation pump safing process, followed by the storing of the air data probes. If hypergolic fuels are not used, the entity bypasses the two processes. Additionally, if hypergolic fuels are used, but the RMLV has autonomous hazardous gas detection, the entity bypasses the air data probe storage process.

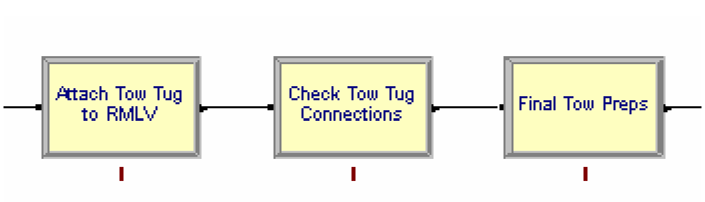
The final process represents the safing of the inertial navigation system (INS). Following this process, the entity proceeds to the towing process.

Segment 3 (Part 2): RMLV Preparation for Transportation



The second portion of the RMLV preparation for transportation occurs in parallel with the safing sequence, and includes several parallel processes. The first parallel process represents actions to place protective covers on various RMLV equipment. The decision module allows designer to determine if protective covers are required to protect the RMLV components during the towing operation. The remaining parallel processes represent actions to position the tow tug and the monitoring of on-board systems.

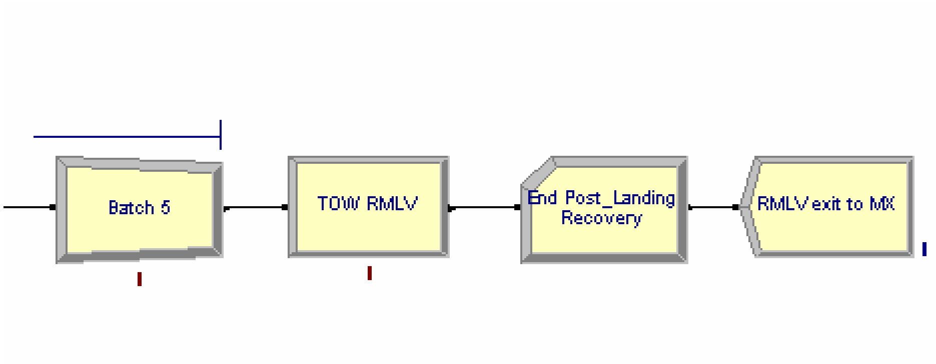
Segment 6: Tow Preparation



The final tow preparations also occur in parallel with the safing sequence. The three processes include hooking the tow tug to the RMLV, checking the connections, and

conducting final preparation actions such as removing chocks, if required. Once these actions, and the actions in Segment 5, are complete the entity proceeds to towing operations.

Segment 7: Towing to the Maintenance Facility



The final segment of the model only represents the towing operation to the maintenance facility, but includes other important modules for the model. The first is a record module which electronically records data on the entity. The second is the dispose module which also electronically records data on the entity, such as total time in system, and disposes of the entity for logic continuity. As a stand-alone model, the disposal function is important, however it will be removed when the model is added to the larger MILePOST model constructed by Captains Pope and Stieglmeier.

Model Verification

Three methods of verification were used for the RMLV post-landing recovery operations model; Arena's internal software debugging utilities, output analysis, and the assertion checking method similar to the methods used by Captains Pope and Stieglmeier. The results of the Arena internal software debugging and output analysis are discussed in Chapter III.

In the assertion checking verification process, the use of resources specific to each process was tracked during forty replications of the model for three separate design decision treatments. In each treatment, the design decisions were made within the rudimentary Excel spreadsheet user interface and recorded. The model was then run and the use of resources tracked. Based on design decisions, specific resources should be used during each replication. The first treatment evaluated answering “no” to all design questions. The second treatment was a simple assessment of the impact of answering “yes” to all questions regarding design decisions. The third treatment evaluated the decision to exclude all design features the author considered to be detrimental to minimizing RMLV regeneration time. Table 4.1 shows the results of the first replication of the first treatment. The first column is the design question considered, the second answer, with a “1” for a “yes” answer and a “0” for a “no” answer. The third column is the resource that would be used based the answer to the design question, and the fourth column is number of times the resource was utilized.

Design Question	**Answer “1” = Yes “0” = No**	**Associated Resource**	**Utilization**
Does APU shutdown automatically?	0	APU GSE	1
Does design include hypergolics?	0	- Forward Safety Assessment GSE - Aft Safety Assessment GSE	0 0
Do internal structures require purge and inerting?	0	Purge GSE	0
External Ground Cooling Required?	0	Cooling GSE	0
Can RMLV return with external stores?	0	External stores separation GSE	0
MPS and RMLV require protective covers?	0	Protective cover GSE	0

Table 4.1: Verification Results from First Treatment

In all assertion checking verification runs the model performed as expected. From these results, the conclusion is the rudimentary user interface is sufficient and the model will run as expected according to the inputs into the user interface.

Model Validation

Two methods were used to validate the model, the Delphi process and comparison of the models performance against the real world system. Both methods were described in Chapter III, the results of each validation process are discussed here.

Delphi Process

The Delphi Process drew from the expertise of professionals in the field of Space Shuttle Orbiter post-landing recovery operations and F-16 fighter aircraft maintenance operations, which include post-landing recovery, and was planned for two review rounds and an optional third round to be conducted only if required. The initial field of invitations included twenty-two individuals from various organizations. In the first round, five reviewers responded. The second round review was only sent to those individuals who responded in the first round. Four participants responded in the second round. The comments in the second round prompted significant changes to the model, so the optional third round was conducted, with two participants responding. The actual documents reviewed by the Delphi panel and their responses can be viewed in Attachment 1. The names of participants and individual responses have been sanitized to protect the integrity and professional image of the individual in accordance with Air Force Institute of Technology requirements for research involving human subjects. All

participants signed a consent form which explained the intent and conduct of the Delphi process prior to their decision to participate.

Comparison to Real World System

The RMLV is in the concept phase, so no real world system exists to compare the model results to, however, the Space Shuttle orbiter is useful as a surrogate for analysis. Using the orbiter data as the baseline for the process duration distributions in the model, and then comparing the model results to the Space Shuttle orbiter post-landing recovery data will offer the best validation of any real world system. The model was run with forty replications to produce enough data to develop useful statistics for the comparison. The basic statistics are presented in Table 4.2 are the combined results from the forty replications for comparison to the Space Shuttle orbiter's actual post-landing recovery.

Mean	3.4303 hours
Standard Error Mean	0.0358 hours
Minimum	3.0364 hours
Median	3.4052 hours
Maximum	3.9859 hours
Standard Deviation	0.2265 hours

Table 4.2: Model Total Post-Landing Recovery Time

The histogram in Figure 4.1 illustrates the distribution of the total post-landing recovery times from the forty replications performed for validating the model.

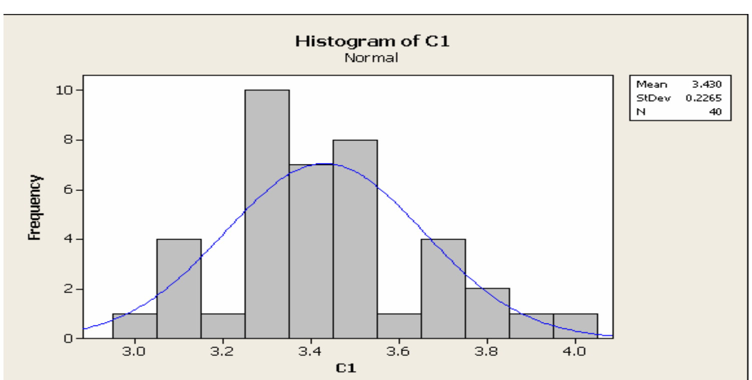


Figure 4.1: Histogram of Model Total Post-Landing Recovery Time

Historically, Space Shuttle orbiter towing operations begin within four hours of landing, and are complete within six hours of landing. Since the RMLV is expected to be an unmanned spacecraft, the time required to service the flight crew for the orbiter can account for the difference in the total duration between real world orbiter post-landing recovery operations performance and the modeled RMLV post-landing recovery operation.

Validation Summary

The Delphi process used in this research was the most important validation tool used in this model. The insights and opinions of the experts participating in the Delphi panel greatly shaped the construct of the model. The secondary validation of comparing to a real-world system, while effect when using distributions derived from data collected on that real-world system, is limited in that it cannot account for the validity of the model if it does not include a similar design to the Space Shuttle orbiter.

Conclusions

The construction of the RMLV post-landing recovery process model revealed several insights to help guide design and development. In general, the simplest design, requiring the fewest ground crew actions and ground support equipment requirements will produce the performance sought by the Air Force. Specifics related to these design decisions include on-board automation of sensors and specific shutdown actions, the elimination of time-consuming ground crew actions by designing the RMLV in such a way that it does not require special handling to protect its components, or to protect the ground crew from hazardous situations that could be avoided with alternative designs.

On-board Automation

The automation of as many processes as practical will shorten the processing time required to recover the RMLV. As observed in comparing the Space Shuttle orbiter and F-16 processes for handling hydrazine powered units, using automated hazardous gas detection speeds processing, eliminating minutes from the recovery process.

Eliminating Special Handling Requirements

The Space Shuttle orbiter requires significant special handling to protect the flight and ground crew personnel from hazardous materials. In particular, hydrazine and its by-products are dangerous to all personnel. In the orbiter it is used to power the auxiliary power unit, and on the F-16 it is used to power the emergency power unit. The elimination of hazardous materials that require special handling will significantly reduce post-landing recovery time for the RMLV. In the NASA root cause analysis of possible technical changes to the Space Shuttle system, fuels requiring special handling were identified as a cause for delays in processing (McClesky, 2005:82).

Simplicity

Simplicity in design and processes goes hand-in-hand with the other recommendations. The simpler the design, such as exchanging the hydrazine powered APU with a battery system, will often drive simpler and quicker ground processing. Additionally, when comparing Space Shuttle orbiter and F-16 processes, the requirements for the purge and cooling processes, and the complexity of those processes adds considerable time to the processing of the orbiter (McClesky, 2005:82). If these processes can be avoided, the RMLV will be able to achieve post-landing recovery times closer to the F-16 process.

The concept of simplicity is not new, in independent studies, Air Force analysts developed recommendations for simplicity in design and processes for space launch systems (London, 1994:96-102). Simplicity in design may not eliminate the requirement for specific processes, but may make servicing the design simpler and faster, reducing the total time for post-landing recovery. Also, complexity in design does not prevent the processes for servicing the RMLV from remaining simple. The F-16 offers an excellent example. The F-16 is a complex system, but the processes required for post-landing recovery are simple and take little time when compared to the processes and time required to conduct post-landing recovery of the Space Shuttle Orbiter.

Recommendations for Future Research

Three recommendations for future research evolved from the conduct of the research for the creation of the RMLV post-landing recovery discrete-event simulation model.

First, the RMLV ground operations model which is the compilation of the model for this study and the models for vehicle maintenance and pre-launch operations, created by Captains Pope and Stiegelmeier respectively, should be combined with flight operations models that evaluate the launch, flight, and return-to-base for the RMLV. The combined flight and ground operations model, constructed with the level of detail for all phases that currently exists in the ground operations models, while complex, will aid RMLV designers to fully evaluate the impact of design decisions on the conduct of the entire RMLV mission.

Second, an assumption in this model was the use of liquid propellants for the fist-stage booster. This assumption guided the development of the model. Another option is

the use of solid rocket fuels for the primary booster. The use of solid rocket fuels will dramatically alter the design of the RMLV, as well as the processes required to service the vehicle in post-landing recovery, maintenance, and pre-launch operations. The basic concept could be a vehicle package that includes all the avionics and guidance systems, and the aerodynamic structures required to accomplish the mission. The solid fuels could be scalable cartages inserted into the vehicle, tailored for the specific mission. A solid rocket design could simplify many ground operations processes, but will also have to be evaluated against flight operations requirements.

Third, cost analysis is an important factor in evaluating the efficacy of any design decision. The subject model for this study did not address cost issues. In future studies, the impact of RMLV design decisions to the cost of operations should be incorporated into the model to provide a full accounting of the critical factors that affect any design decision.

Finally, there are opportunities for investigating the methods of incorporating process simplicity and efficiency into complex systems. When comparing the Space Shuttle orbiter and F-16 processes, it is clear that some processes are similar, with nearly identical purposes, but vary greatly in complexity and duration. Researching the conduct of critical processes in the context of RMLV design and component design, can potentially yield significant improvements in the simplicity and duration of processes required for RMLV regeneration.

Summary

The purpose of this study was to develop a discrete-event computer simulation model to assist the Air Force Research Laboratory, Air Vehicles Directorate in the

evaluation of the impact of various design decisions on the time to perform post-landing RMLV recovery operations. This study has demonstrated the place the RMLV concept holds within the US National Space Transportation Policy, Air Force doctrine, and AFSPC initiatives. The analysis of Space Shuttle orbiter and F-16 post-landing recovery operations reveals general principles designers should consider when conducting production runs and analysis using the model to evaluate design alternatives. The final RMLV design will have to meet a broad range of requirements. The real challenge for designers is not to optimize the post-landing recovery operation, but to optimize system performance across all phases of operation, launch, flight operations, post-landing recovery, vehicle maintenance, and pre-launch. Design decisions that will optimize the post-landing recovery operations may have a greater negative impact on another operational phase than the positive impact to post-landing recovery. Finally, this study cannot answer all questions regarding the best approach for evaluating design alternatives. Future research should evaluate all phases of operation, cost, and dramatically different design options not offered in this study.

Attachment 1: Delphi Panel, Round 1 Review and Responses

REUSABLE MILITARY LAUNCH VEHICLE LOGISTICS: POST-LANDING RECOVERY OPERATIONS MODEL DELPHI PANEL REVIEW #1

Delphi Panel Participants,

Thank you for your willingness and time to participate in this research on the post-landing recovery operations model for the Reusable Military Launch Vehicle (RMLV). In the following pages you will find the processes and flow of the initial model for your review. Some points I would like to highlight to help guide your analysis of the model are first, this model is only intended to represent the processes from the point of wheels-stop on the runway to the end of towing outside the vehicle maintenance facility. Second, I am primarily concerned with your comments regarding the following issues:

1. Are the processes represented appropriate?
2. Are all appropriate processes included in the model?
3. Are the processes represented to the appropriate level of detail?
4. Is the flow/order of the processes appropriate?
5. Are parallel processes identified appropriately?
6. Are there opportunities to consolidate processes in the model and still accurately represent the system?

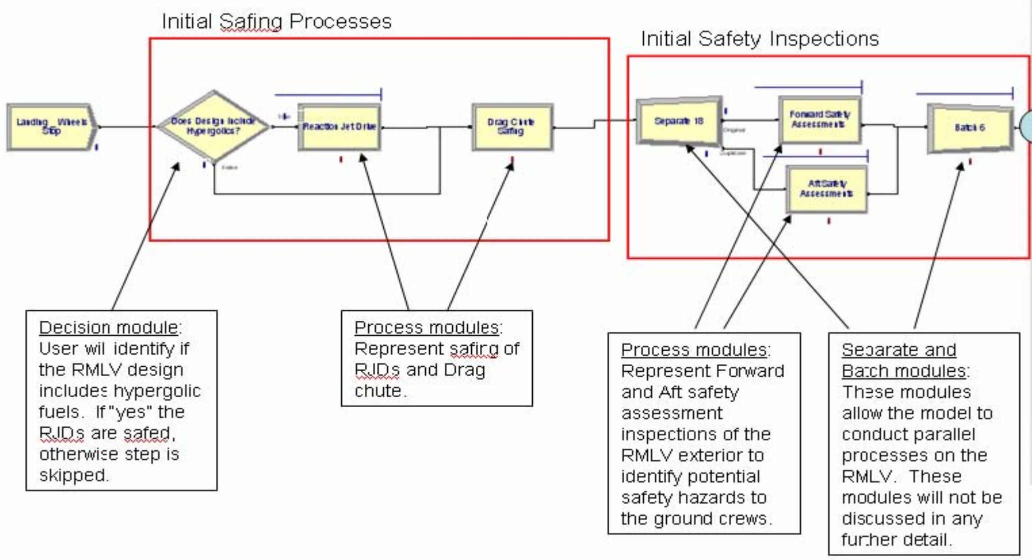
Outside of these primary questions, I am interested in any other comments you may have regarding this effort, but only your comments regarding the actual model will be used in the research.

I will be looking for responses on 17 March 2006 with the intent of consolidating and incorporating comments into the model and sending out a second, and hopefully final, model for your review by 3 April 2006. As a final note, without a signed informed consent letter I cannot include your comments in the study, so please send a signed copy as requested in the email accompanying the letter. Thank you again for your attention and assistance in this study of the RMLV post-landing recovery operations model.

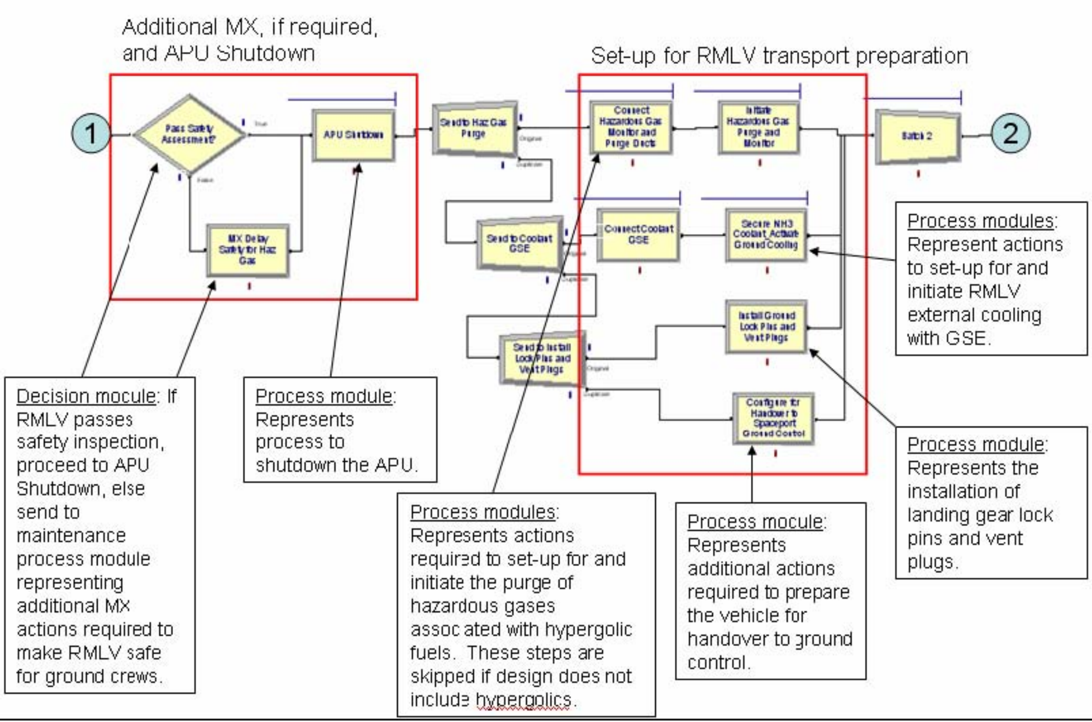
Very Respectfully,

MICHAEL MARTINDALE, Major, USAF
Air Force Institute of Technology
Department of Operational Sciences
Michael.martindale@afit.edu

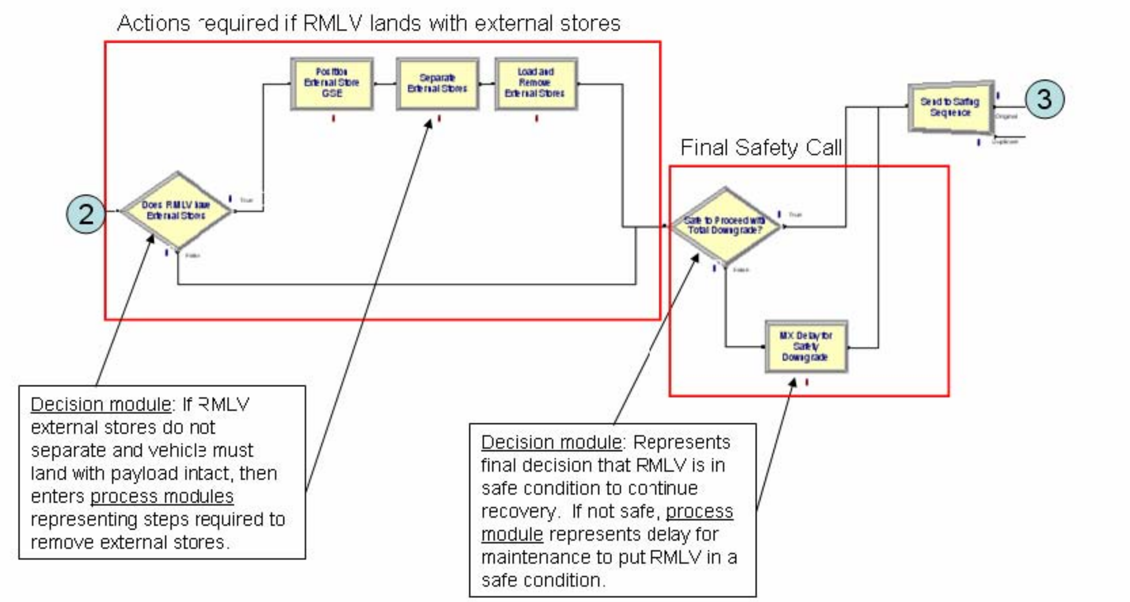
Initial Safing and Safety Assessment Inspections



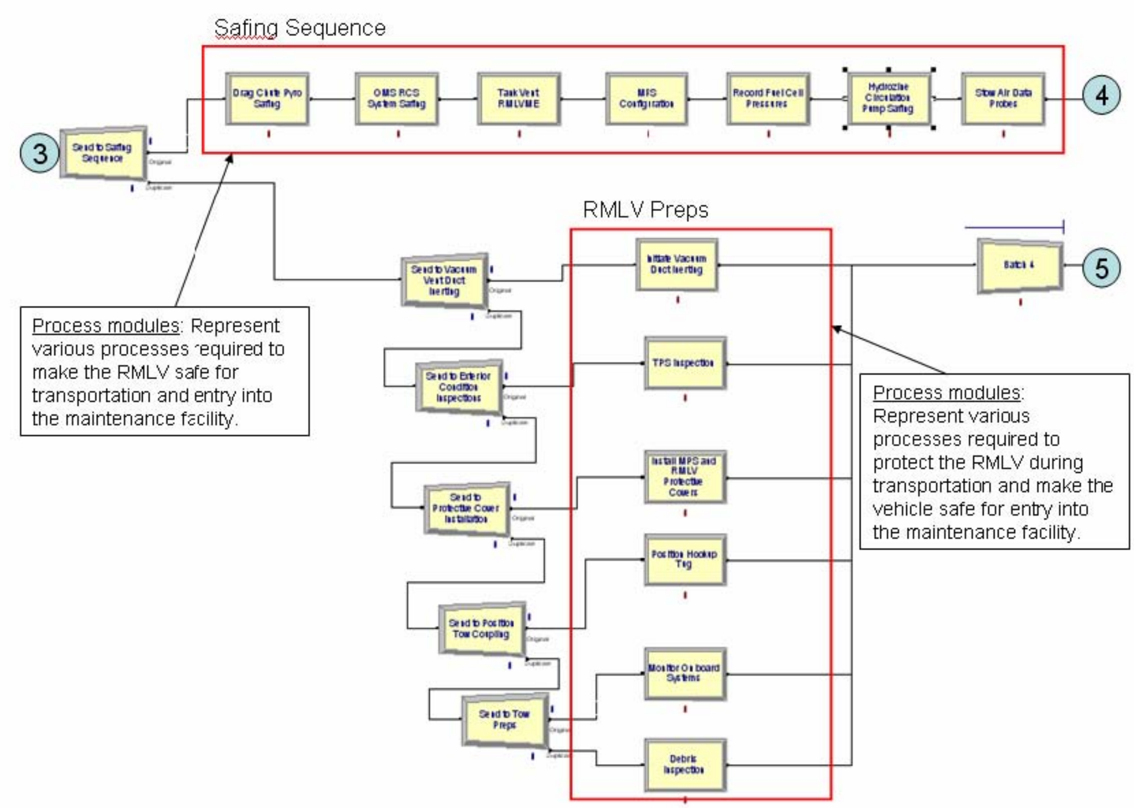
Additional Maintenance Actions to Create Safe Environment for Ground Crews, and Set-up for Preparing RMLV for Transport to Maintenance Facility

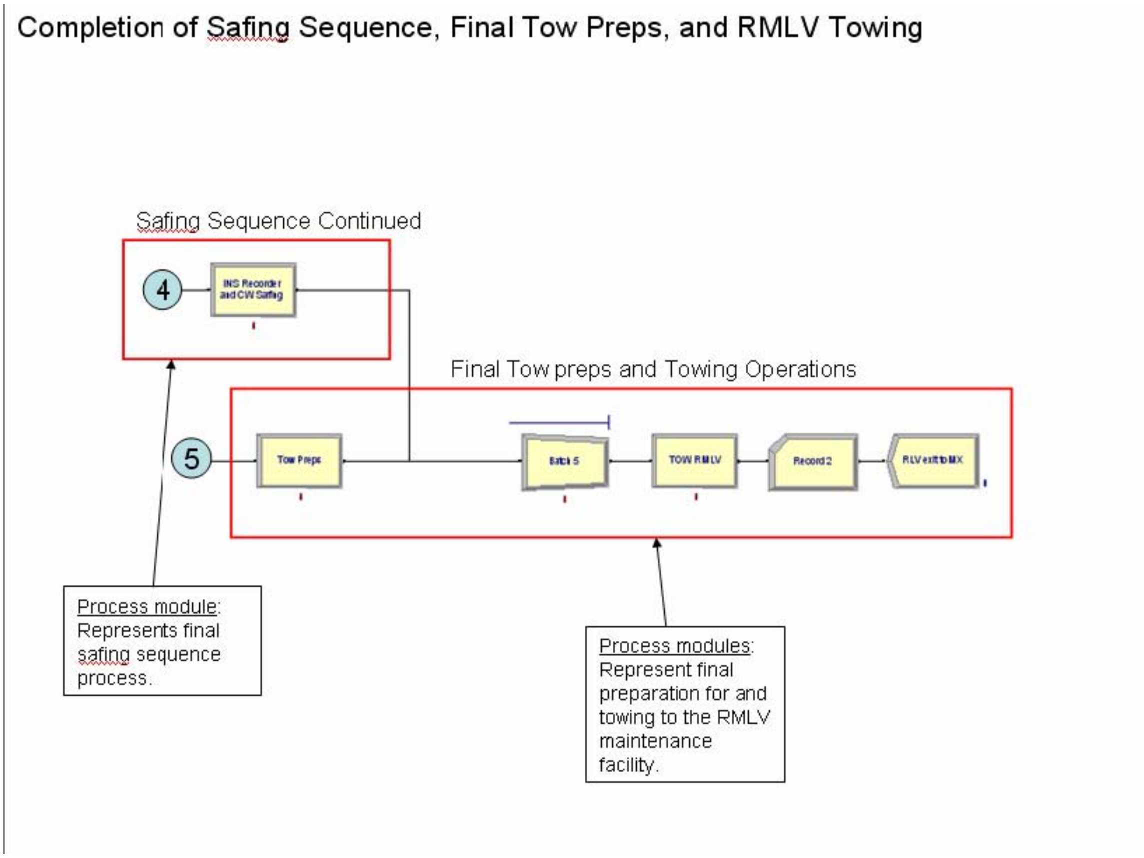


Incident of RMLV landing with external stores, and final safety call



Safing Sequence and Final RMLV Pre-Tow Preparations





Delphi Panel Participant Comments from Round 1

Reviewer 1:

Comment: "Pass Safety Assessment?" If you are doing the "Forward Safety Assessments" and "Aft Safety Assessments" prior to Node 1 (before the Fwd and Aft assessment are batched) would you do this pass test decision then and for each parallel process? If not then you might be waiting unnecessarily to start the additional maintenance for the failed assessment.

Action: I am operating on the assumption that the entire safety assessment must pass before proceeding with additional recovery actions. Part of my reasoning is based on the absence of a crew which would force urgency in proceeding, as it is, the ground crew's safety is the primary concern. If my reasoning is predicated on a false assumption, then please let me know and the model can be changed.

Comment: You might consider putting the "Pass Safety Assessment?" and "MX Delay Safety for Haz Gas in a loop back to before the decision block. The reason for this is that the Mx process may not fix the safety concern or could possibly cause some additional safety concerns (Maintenance induced failure) that would need to be addressed. In the

“MX Delay for Haz Gas” block, is hazardous gas the only safety concern that would cause a failed safety assessment?

Action: Incorporated into the model.

Comment: If the booster returns with the payload, would this require a possible path and decision in the model where the vehicle may need to be towed to the integration facility?

Action: This is a critical system design consideration I had not thought of prior. Essentially, it is the tradeoffs between designing and building equipment to remove and handle the payload on the runway as a part of recovery versus using the integration facility at the expense of using the facility to prepare a separate RMLV and payload for launch. From a modeling perspective this is fairly easy to incorporate, but really it is a larger system design issue. I am interested in others comments regarding system design. Either way of removing the payload in this contingency will work, perhaps the model needs options to do it either way, on the runway using specialized GSE, or in the integration facility. Comments?

Comment: How is the “Drag Chute Pyro Safing” in the Safing Sequence different than the “Drag Chute Safing” during the initial Safing Processes?

Action: Incorporated into the model.

Comment: I’m not 100% sure but I think that Hydrozine is a Hypergol. Shouldn’t this have been safed prior to Node 2 or at least have a decision block around this if Hypergols are not used?

Action: Incorporated into the model.

Reviewer 2:

Comment: RJDs will most likely be required for any reentry vehicle, should assume they are there.

Action: Incorporated into the model.

Comment: If non-toxic fuels for RJD (peroxide), then safe but no ground assessment required. If toxic fuels, then safe and ground assess for 0 toxic residuals/leaks.

Action: Incorporated into model and discussion.

Comment: APU for Shuttle powers hydraulics for flight controls, if that module is intended to pertain to flight controls, it should be powered down.

Action: Incorporated into discussion.

Comment: Electrical power for avionics is from fuel cells, should remain powered thru total safing. Generally, some form of GSE cooling would be required while powered.

Action: Incorporated into discussion.

Comment: Vehicle purge is for both toxics and explosives. Accumulations of oxidizers, fuels or toxics could pose a hazard to the vehicle/gnd personnel.

Action: Incorporated into model and discussion.

Comment: Purge on the Shuttle is also for structural cooling post reentry, life cycle issue with the structure.

Action: Incorporated into discussion.

Comment: As I mentioned earlier, gnd cooling is for avionics which remain powered during gnd operations.

Action: Incorporated into discussion.

Reviewer 3:

Comment: Does the safing sequence include the time it might take people to get to the vehicle?

Action: Yes, based on the assumption that the entire ground crew is ready and in position at wheels stop and begin approaching the vehicle after it passes safety assessment.

Comment: What does “MX” mean? Maintenance?

Action: Yes.

Comment: Tow preps could be expanded a little more – bring out vehicle for towing, attach to RMLV, check connection, etc.

Action: Incorporated into the model.

Reviewer 4:

Comment: No comments.

Action: None.

Reviewer 5:

Comment: From our phone conversation it looks like the overall flow diagrams are correct.

Action: None.

REUSABLE MILITARY LAUNCH VEHICLE LOGISTICS:
POST-LANDING RECOVERY OPERATIONS MODEL
DELPHI PANEL REVIEW #2

Delphi Panel Participants,

Thank you for your continued willingness to participate in this research on the post-landing recovery operations model for the Reusable Military Launch Vehicle (RMLV). In the following pages you will find the processes and flow of the model modified based on your comments from the first review. As a reminder, this model is only intended to represent the processes from the point of wheels-stop on the runway to the end of towing outside the vehicle maintenance facility. Second, I am primarily concerned with your comments regarding the following issues:

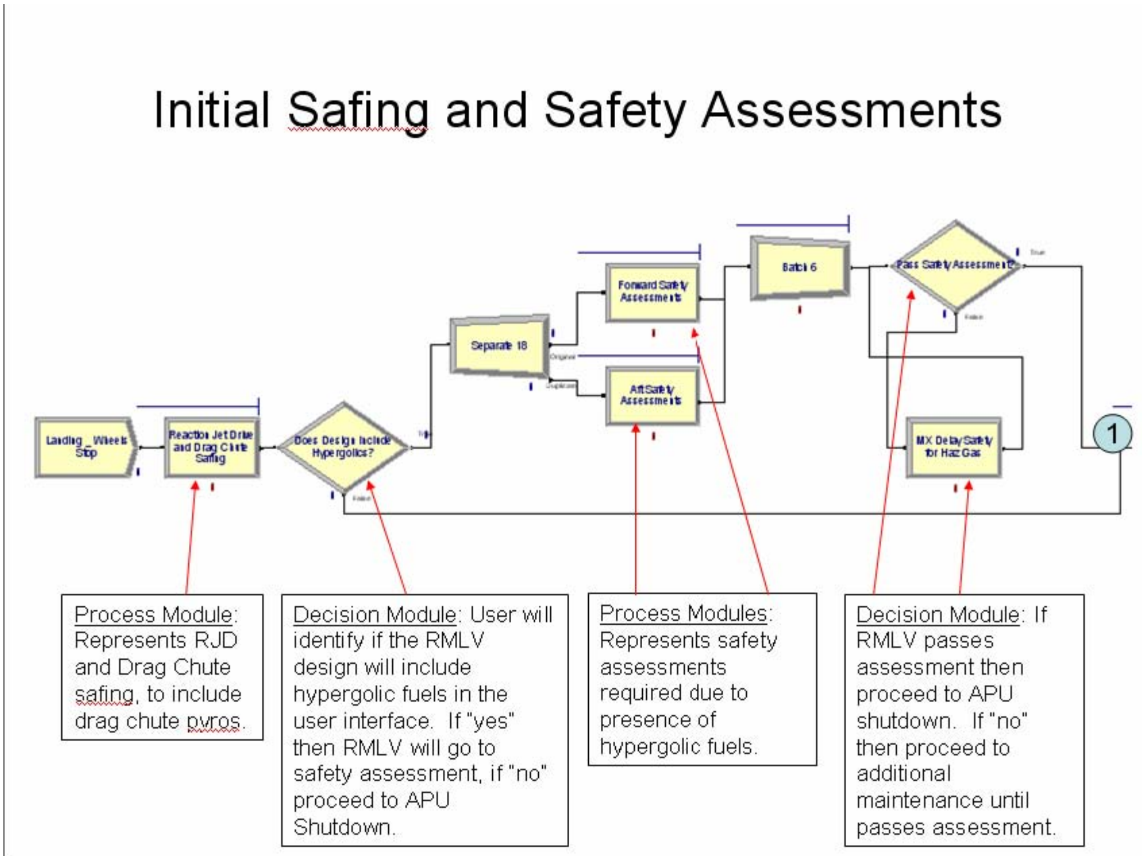
1. Are the processes represented appropriate?
2. Are all appropriate processes included in the model?
3. Are the processes represented to the appropriate level of detail?
4. Is the flow/order of the processes appropriate?
5. Are parallel processes identified appropriately?
6. Are there opportunities to consolidate processes in the model and still accurately represent the system?
7. Were your previous comments accurately incorporated into the model?

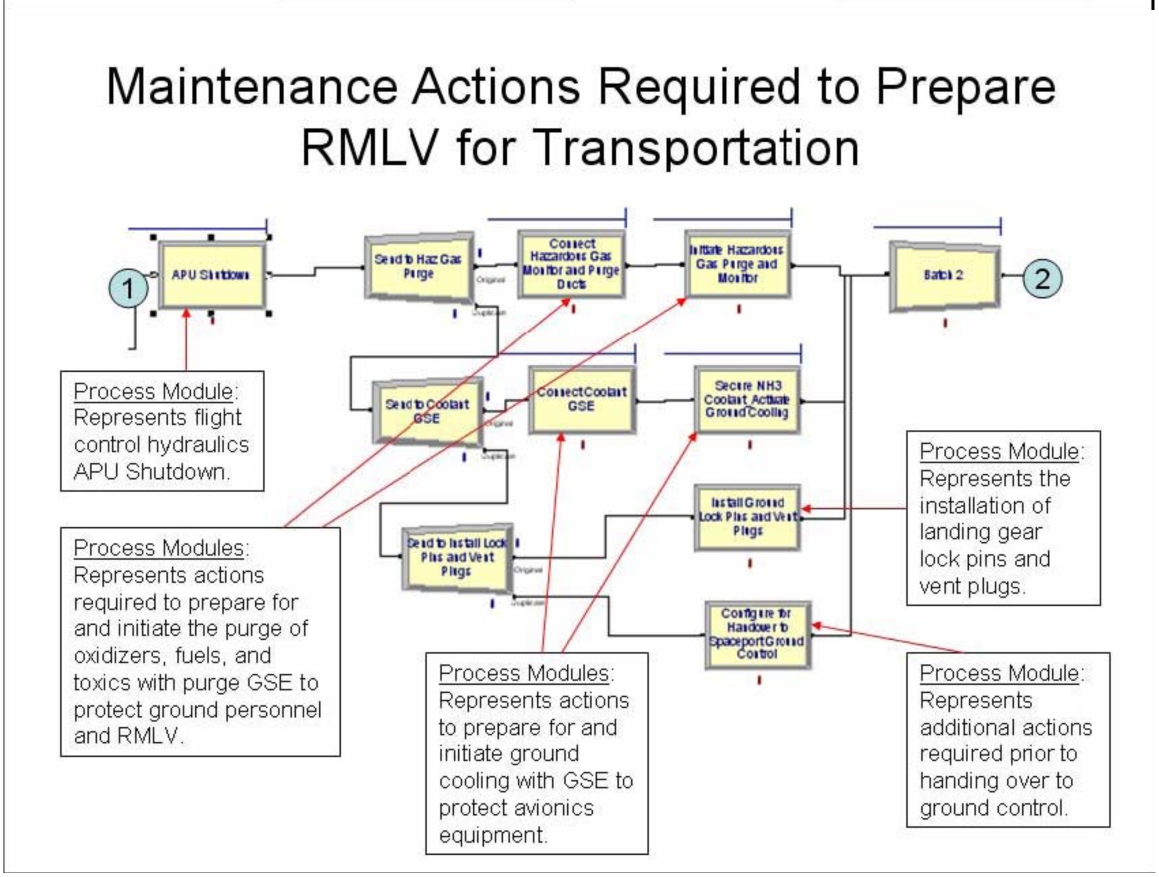
Outside of these primary questions, I am still interested in any other comments you may have regarding this effort, but only your comments regarding the actual model will be used in the research.

I will be looking for responses on 20 April 2006. This is intended to be the final review, however, if there are significant issues with the model a third review may be required. I have received informed consent from most of you, and I owe further contact information to those who have not sent it yet, look for the information on your email. I am a student with knowledge of modeling and space operations, but with no real practical experience in this area, so I thank each of you for the benefit of your knowledge and effort in supporting me in my research to build the RMLV post-landing recovery operations model.

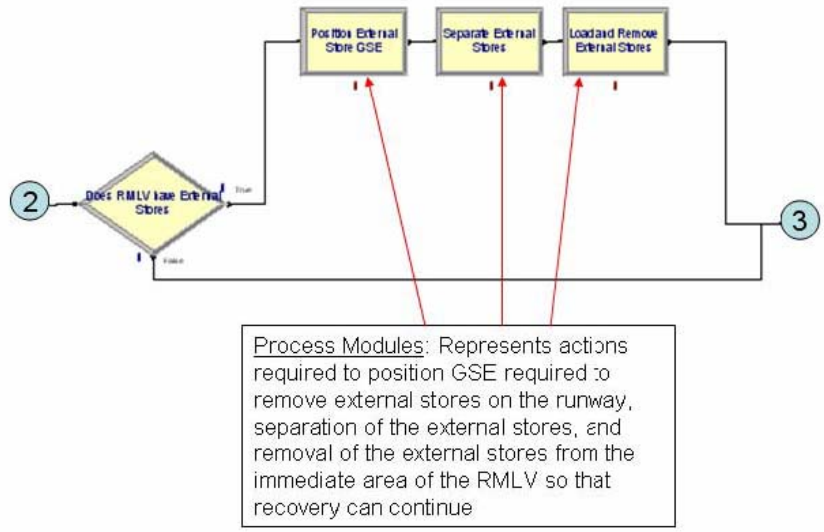
Very Respectfully,

MICHAEL MARTINDALE, Major, USAF
Air Force Institute of Technology
Department of Operational Sciences
Michael.martindale@afit.edu

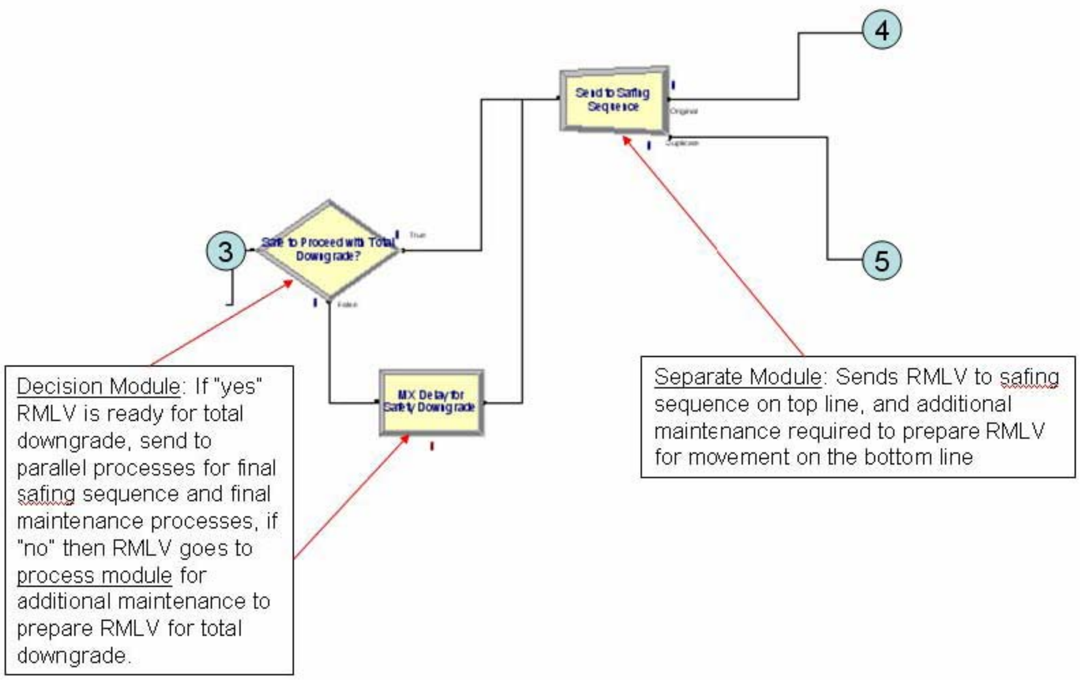

Initial Safing and Safety Assessments
Landing _Wheels Stop
Reaction Jet Drive and Drag Chute Safing
Does Design Include Hypergolics?
Separate 18
Forward Safety Assessments
Aft Safety Assessments
Batch 6
Pass Safety Assessment?
MX Delay Safety for Haz Gas
1
Process Module: Represents RJD and Drag Chute safing, to include drag chute pyros.
Decision Module: User will identify if the RMLV design will include hypergolic fuels in the user interface. If "yes" then RMLV will go to safety assessment, if "no" proceed to APU Shutdown.
Process Modules: Represents safety assessments required due to presence of hypergolic fuels.
Decision Module: If RMLV passes assessment then proceed to APU shutdown. If "no" then proceed to additional maintenance until passes assessment.


Maintenance Actions Required to Prepare RMLV for Transportation
1
APU Shutdown
Send to Haz Gas Purge
Connect Hazardous Gas Monitor and Purge Ducts
Initiate Hazardous Gas Purge and Monitor
Batch 2
2
Send to Coolant GSE
Connect Coolant GSE
Secure NH3 Coolant Activate Ground Cooling
Send to Install Lock Pins and Vent Plugs
Install Ground Lock Pins and Vent Plugs
Configure for Handover to Spaceport Ground Control
Process Module: Represents flight control hydraulics APU Shutdown.
Process Modules: Represents actions required to prepare for and initiate the purge of oxidizers, fuels, and toxics with purge GSE to protect ground personnel and RMLV.
Process Modules: Represents actions to prepare for and initiate ground cooling with GSE to protect avionics equipment.
Process Module: Represents the installation of landing gear lock pins and vent plugs.
Process Module: Represents additional actions required prior to handing over to ground control.

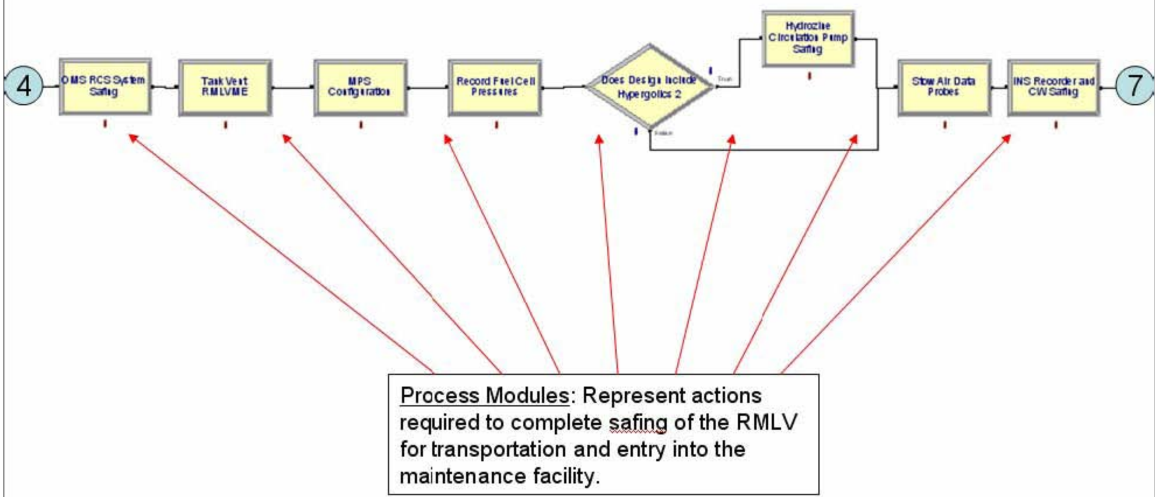
Incident of RMLV Landing with External Stores



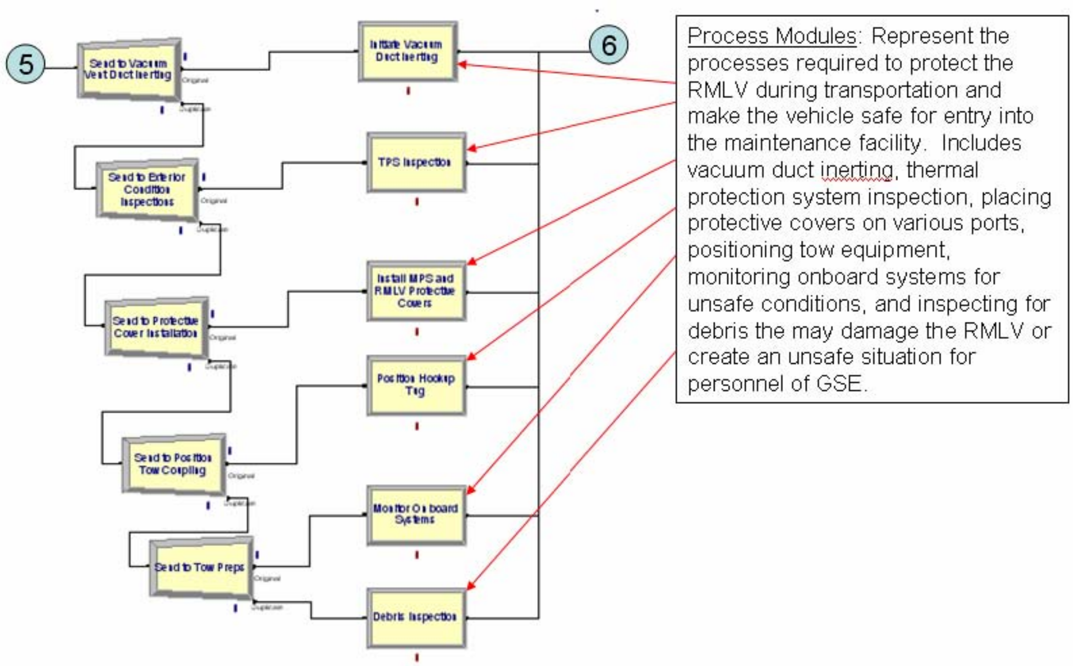
Final Safety Call



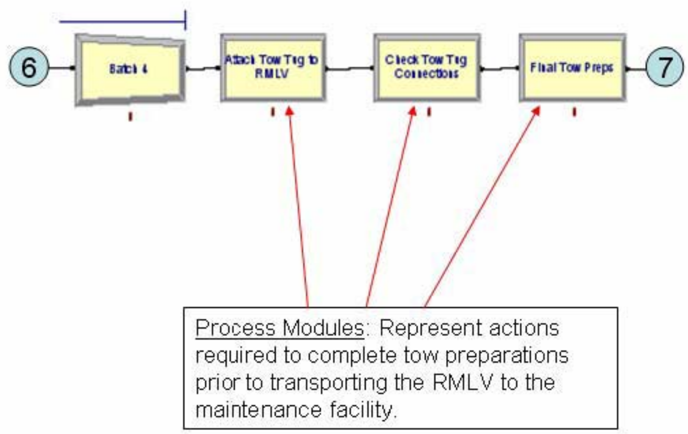
Safing Sequence



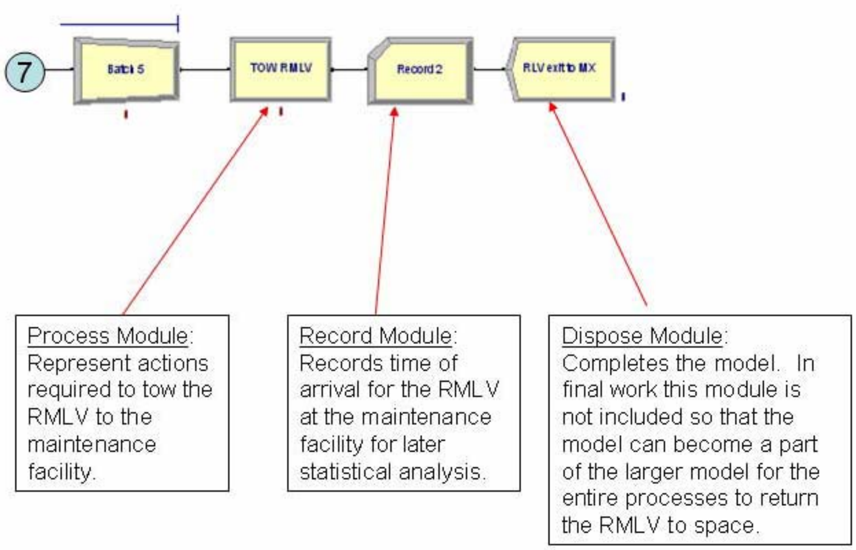
RMLV Preparation for Transportation



Final Tow Preparations



Towing Operations



Delphi Panel Participant Comments from Round 2

Reviewer 1:

Comment : If you have a problem with hypergolic leaks – why would you want the APU to continue to run until maintenance actions are complete?
I don't know how the F-16 operates their hydrazine APU but for the shuttle orbiter, there is only a limited supply of fuel on board and the APU system is no longer needed after wheels stop. The APU system would also be one of the primary leak locations causing the anomaly in the first place. I would suggest the proper sequence would be to move the APU shutdown just after wheels stop before any ground personnel approach. You would still have electrical power from batteries or fuel cells to monitor the flight systems and down load any health management data for the ground crew.
The Does Design include Hypergols block and forward and aft assessment blocks would remain the same just move shutdown APU between Wheels stop and Reaction Jet and Drag chute Safing (or between Safing block and Does Design include blocks).

Action: Incorporated comment in to the model by moving the APU shutdown process as recommended.

Comment: Page 2 contains a lot of work that adds significant time to this process for the sole purpose of giving you more time to work on the vehicle on the runway. If the vehicle were capable of self assessment for leaks and capable of self taxi to the maintenance hanger (UAV's can do this today) why stop and connect purges and coolant loops that now become part of a convoy for moving the vehicle to the maintenance bay? The vehicle purge on the shuttle orbiter is required because the thermal tiles radiate heat in all directions (equally into the wing box and to the outside) and the orbital frame is low temp aluminum – the wing box would yield if the orbiter sat too long after re-entry without a purge to carry the heat away. If you've got high temperature skin and hot structure underneath, I suspect you would not need a vehicle purge on the runway. It depends on your thermal load (flight profile) and the TPS/wing structure materials. You may want a vehicle purge as it gets close to the maintenance bay for a final purge of noxious gases but try to eliminate the convoy option. You may want to add a couple of if/then branches for hot structure yes proceed to lock pin insertion, no, hook up vehicle purge. The same for ground cooling: If Avionics and fuel cells require active cooling within 30 minutes, then hook up coolant loop, if no, proceed to lock pin insertion.

Action: Decision modules added to the model to allow for inclusion of hot structures and safety self-assessments on the RMLV.

Comment: Before the 'ready for downgrade decision block' need to address the safing of the LOX tank on board. This block appears to be later in the Safing sequence – you may not have that long.

Liquid Oxygen (LOX) is a cryogenic fluid (very cold liquid) that wants desperately to return to it's natural gaseous state and atmospheric pressure and temperature. Any LOX left over in the propellant tank after rocket engine shutdown will begin to warm up and pressurize the flight tank until the tank no longer contains liquid and the ullage gas and tank warms up to ambient temperature. Active cycling of the tank vent valve or relief valve will be necessary to control this rising pressure in the tank. During the flight to the landing area, the left over LOX should be drained to the atmosphere. This becomes rather tricky in that, the flight propellant tanks are typically pressure stabilized tank to handle flight structural loads so dropping the pressure too far will result in a very bad day. The most probable scenario this vehicle will have to deal with is the venting of the tank at least once after wheels stop and close monitoring of the tank until the vehicle can be drained and purged. This will probably be done in the maintenance facility or an intermediate safing facility between the runway and maintenance hanger. The shuttle does not have to deal with this per se; The propellant tanks are disposable (the External Tank) that breaks up and falls into the Indian Ocean after main engine cut-off. 100% oxygen environment can be very dangerous with hot things in close proximity; we've burned a few cars to the ground because of an oxygen rich atmosphere so the safety convoy will have to be careful.

Action: LOX safing actions incorporated into the model.

Comment: In the safing sequence you have 'record fuel cell pressures' Running fuel cells will be adding a lot of heat internal to the vehicle – driving the need for the ammonia cooling system in item 2 above. If you could get the vehicle on ground power as soon as possible after wheels stop, this could take another element of a long initial safing period out of the equation. Think of an airliner pulling into the gate, switching to ground power and shutting down the APU's and engines quickly. Also, this vehicle may be using batteries instead of fuel cells (less than an hours flight time from T-0, probably should account for both scenarios – if fuel cells used, etc.

Action: Incorporated decision module to determine need for cooling based on existence of fuel cells. This will be reflected in the GUI coding for the user.

Comment: Under RMLV Prep for Transport:

a. Leave TPS inspection and debris inspection blocks for the maintenance hanger activity. May want to add a preliminary inspection block on first page but this should not be a long or detailed inspection – just looking for gross damage or something leaking on the ground.

b. Same with protective cover inspection, why bring out service platforms out on to the runway when you could install them as soon as your in the maintenance bay where all you access platforms are already staged.

c. I don't understand the vacuum vent duct inerting. Vacuum inerting of the Orbiter MPS system is done on orbit to the vacuum of space where there is no delta pressure to cause damage to flight weight systems and the propellant residuals can evaporate or sublimate to space safely. If you are

> looking to safe the LOX propellant system, you would typically purge your oxygen system with gaseous nitrogen. Again I don't think this would be done on the tarmac but rather at a safing station later in the flow or as soon as it is connected inside the maintenance facility.

Action: Incorporated decision modules to give designers options regarding protective covers and vacuum ducting. Reflected the superficial nature of the TPS and debris inspections as was originally intended.

Comment: Overall, I think you're doing a very good job capturing all the things that need to be addressed on the tarmac before the vehicle heads to the maintenance facility. Keep in mind your model will eventually be used to help drive the design of the vehicle itself so your model needs to ask a lot of 'if vehicle uses hypergols' or 'if vehicle uses fuel cells' type questions so that the designer knows he pays a penalty in turnaround time if his vehicle is too complex. The simplest vehicle that we've been able to imagine is one that a pair of technicians could approach with a tug and be notified on their laptop or radio that it's safe to approach. They put in the gear locking pins, hook up the tow bar and ground power and data cables to the front wheel well and pull the vehicle to a safing station between the runway and maintenance facility for purge and inerting of the LOX tank. The vehicle would go on external power from the tug as soon as it's hooked up. APU's would be shut down automatically at wheels stop and fuel cells, if used, would be shut down as soon as ground power established. The vehicle should be on the move in less than 5 minutes from wheels stop. The more complex the vehicle, the more time, people and support vehicles are needed to make it safely to the maintenance hanger. That's what your model will show the designers.

Action: None.

Reviewer 2: First round comment:

> "If the booster returns with the payload, would this require a possible path and decision in the model where the vehicle may need to be towed to the integration facility?"

Your action mentions a critical system design and this is something I did not consider but it seems as though this step might be moot. Since we are currently concerned with a hybrid launcher (Expendable upper stage) just the booster should be modeled for turnaround. This said the booster will never return with a payload. To accommodate this capability, the booster would have to be designed to land with the payload which would drive the weight and size of the vehicle up which will negatively impact the life cycle costs. This payload removal step would most likely come into play for a reusable upper stage but this probably will not be considered until after a hybrid launcher is flying.
Action: RMLV design is still in its infancy, so the model now includes a decision module that will give designers the option to make the RMLV capable of returning with external stores should it experience some type of contingency, or not have the capability based on size and complexity limitations.

Reviewer 3: No comments.

Reviewer 4: No comments.

Reviewer 5: No comments.

NOTE: Reviewer number designations are not consistent between reviews to ensure anonymity.

**REUSABLE MILITARY LAUNCH VEHICLE LOGISTICS:
POST-LANDING RECOVERY OPERATIONS MODEL
DELPHI PANEL REVIEW #3**

Delphi Panel Participants,

Let me start by saying thank you once again for your willingness to participate in this research on the post-landing recovery operations model for the Reusable Military Launch Vehicle (RMLV). In the following pages you will find the processes and flow of the model modified based on comments from the second review. Originally I planned on only two reviews, however some important comments came in the second review that necessitated a third round. Unfortunately, the third round must be abbreviated with regard to time. I understand that I have asked a lot from the participants and respect the fact you may no longer have time to commit to this project. If that is the case please simply provide a negative reply via email. If you can commit just a little more time, please review the process flows below and provide any additional comments. The purpose is the same as earlier reviews, to answer the following questions:

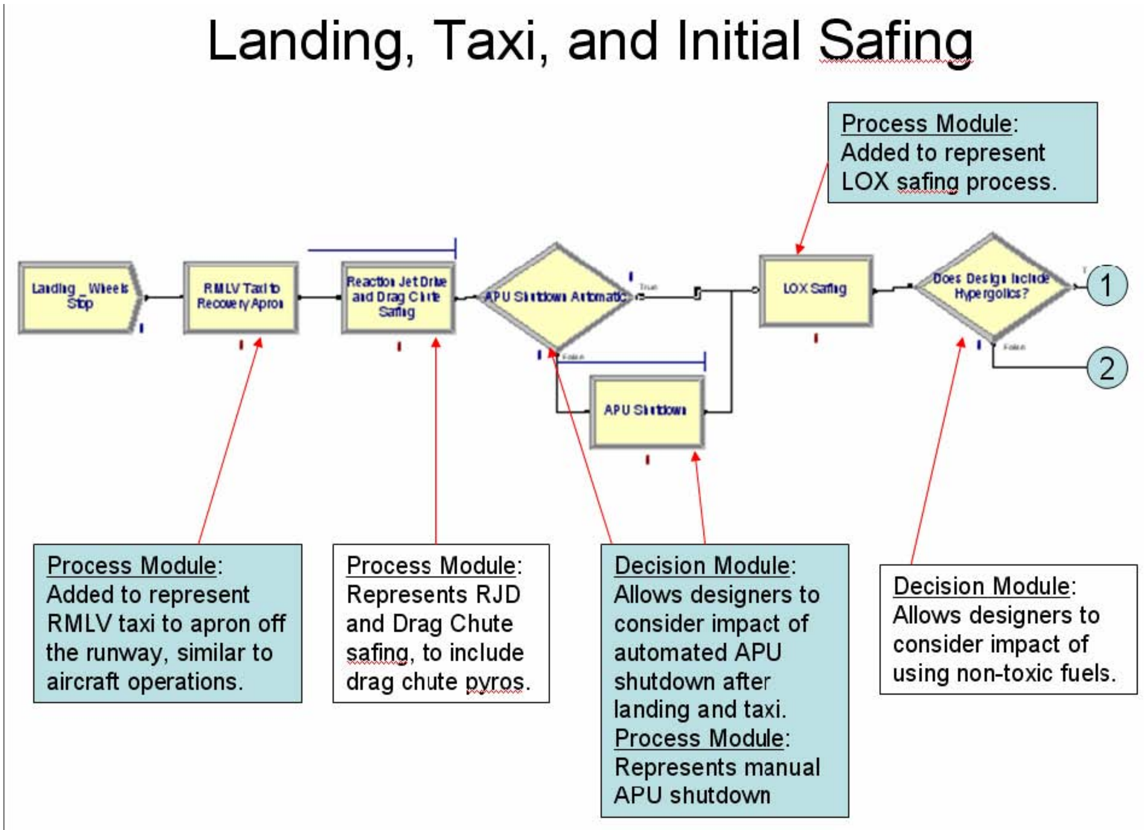
1. Are the processes represented appropriate?
2. Are all appropriate processes included in the model?
3. Are the processes represented to the appropriate level of detail?
4. Is the flow/order of the processes appropriate?
5. Are parallel processes identified appropriately?
6. Are there opportunities to consolidate processes in the model and still accurately represent the system?
7. Were your previous comments accurately incorporated into the model?

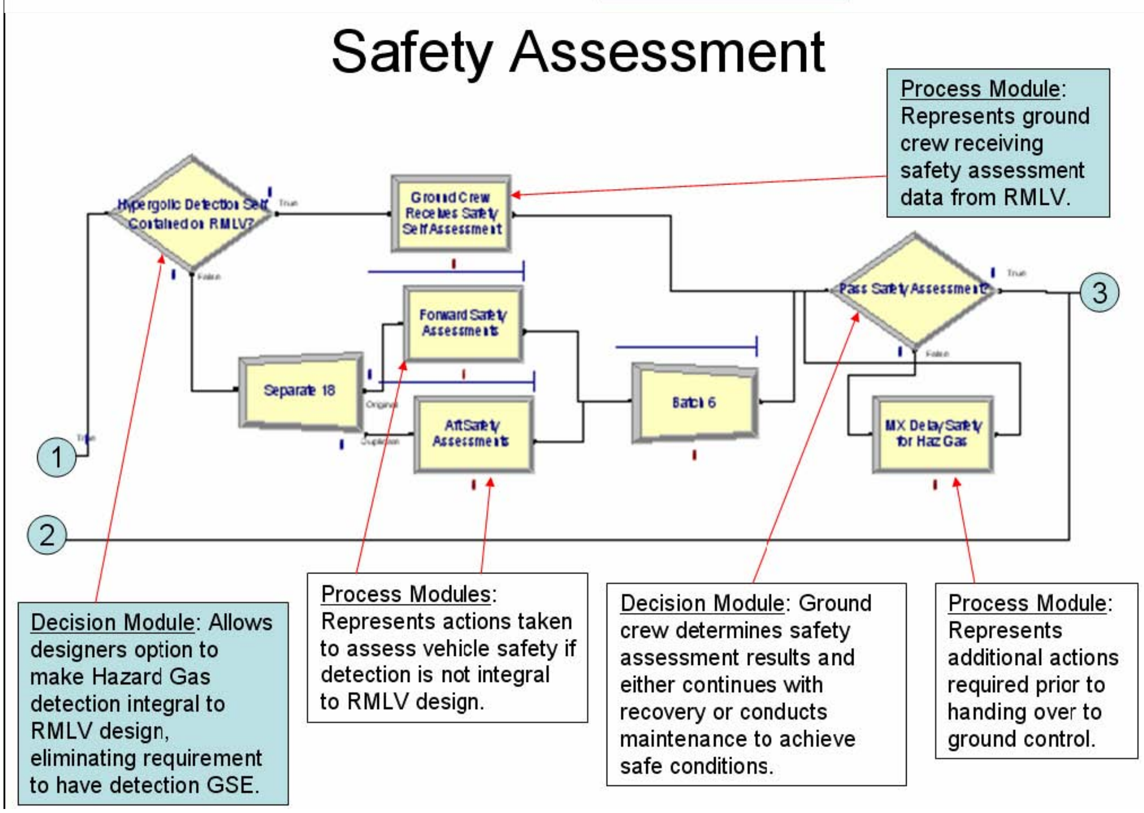
The most recent changes reflect additional design decisions not previously considered (highlighted in blue), but do not significantly change the content of the model. The design decisions will allow some portions of the processes to be by-passed if appropriate.

As I said before, the timelines are compressed for this review, so I will be looking for comments or negative replies no later than 11 May. This will allow me time to incorporate your comments and complete the verification of the changes in the model on time for project completion. Thank you for in supporting me in my research.

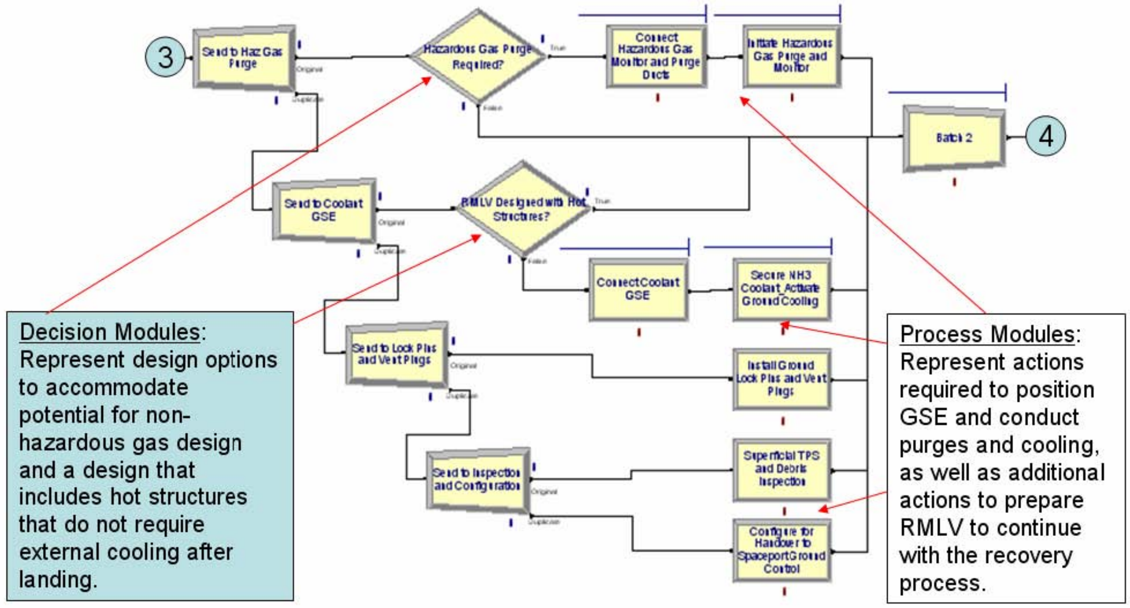
Very Respectfully,

MICHAEL MARTINDALE, Major, USAF
Air Force Institute of Technology
Department of Operational Sciences
Michael.martindale@afit.edu

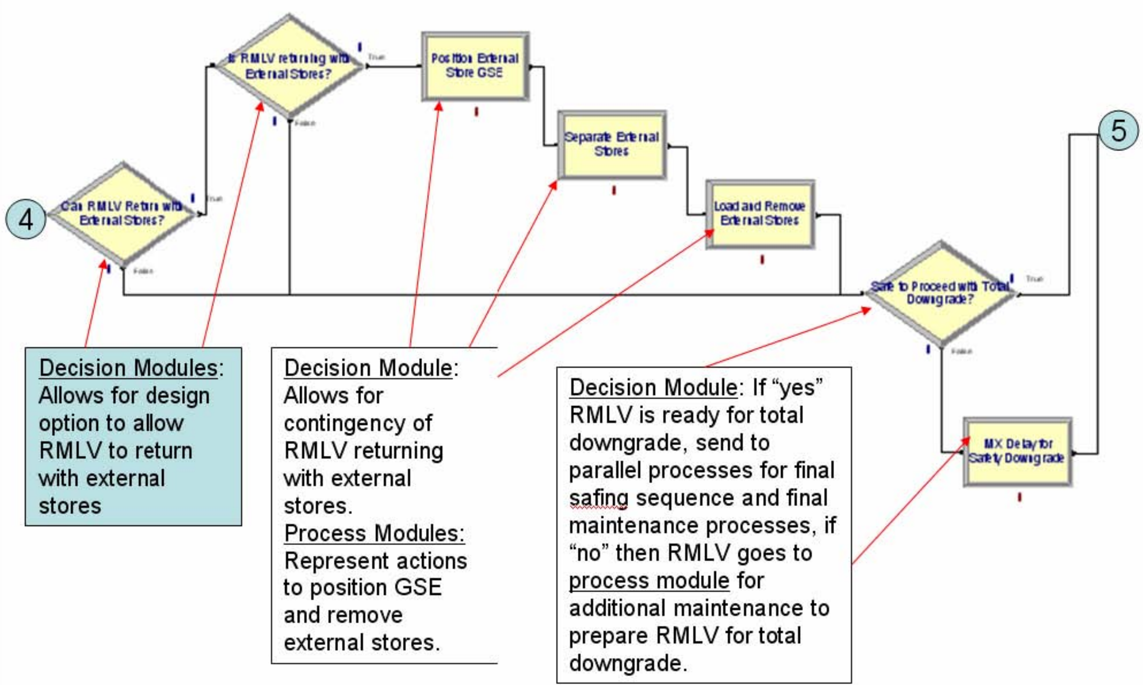

Landing, Taxi, and Initial Safing
Process Module: Added to represent LOX safing process.
Landing _ Wheels Stop
RMLV Taxi to Recovery Apron
Reaction Jet Drive and Drag Chute Safing
APU Shutdown Automatic
True
False
APU Shutdown
LOX Safing
Does Design Include Hypergolics?
1
2
Process Module: Added to represent RMLV taxi to apron off the runway, similar to aircraft operations.
Process Module: Represents RJD and Drag Chute safing, to include drag chute pyros.
Decision Module: Allows designers to consider impact of automated APU shutdown after landing and taxi.
Process Module: Represents manual APU shutdown
Decision Module: Allows designers to consider impact of using non-toxic fuels.


Safety Assessment
Process Module: Represents ground crew receiving safety assessment data from RMLV.
Hypergolic Detection Self Contained on RMLV?
True
False
Ground Crew Receives Safety Self Assessment
Separate 18
Forward Safety Assessments
Aft Safety Assessments
Batch 6
Pass Safety Assessment?
MX Delay Safety for Haz Gas
1
2
3
Decision Module: Allows designers option to make Hazard Gas detection integral to RMLV design, eliminating requirement to have detection GSE.
Process Modules: Represents actions taken to assess vehicle safety if detection is not integral to RMLV design.
Decision Module: Ground crew determines safety assessment results and either continues with recovery or conducts maintenance to achieve safe conditions.
Process Module: Represents additional actions required prior to handing over to ground control.

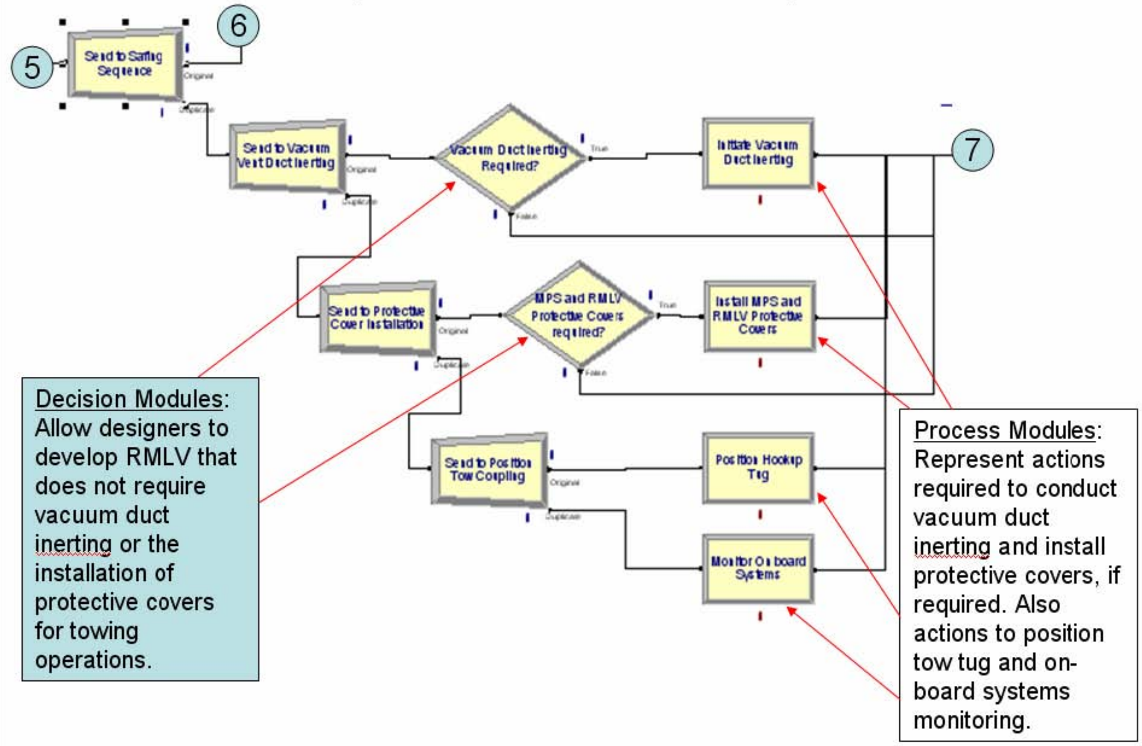
Maintenance Actions Required to Prepare RMLV for Transportation



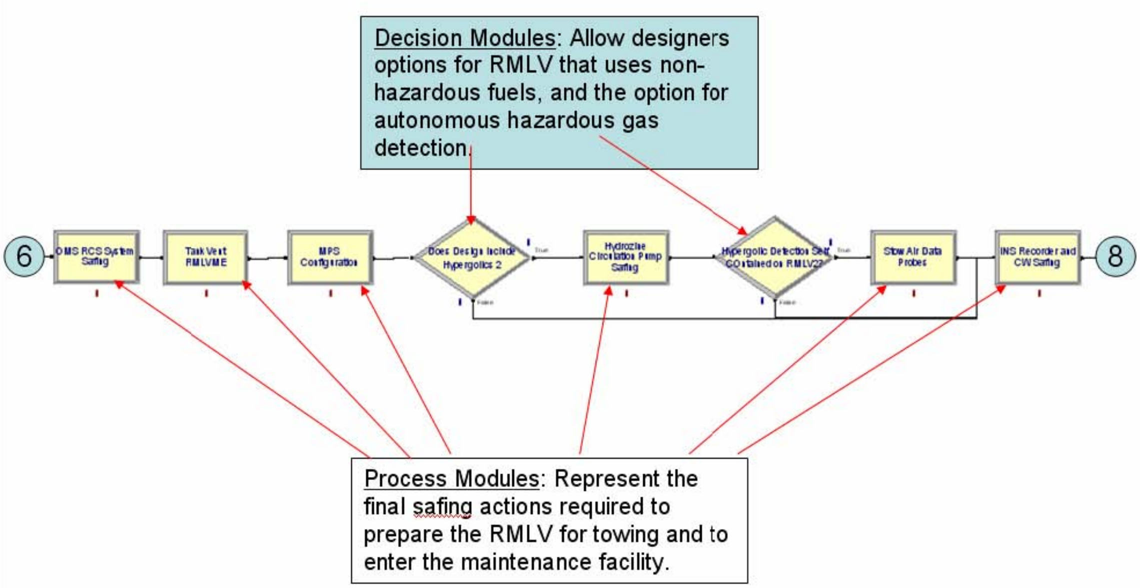
External Stores and Final Safety Call



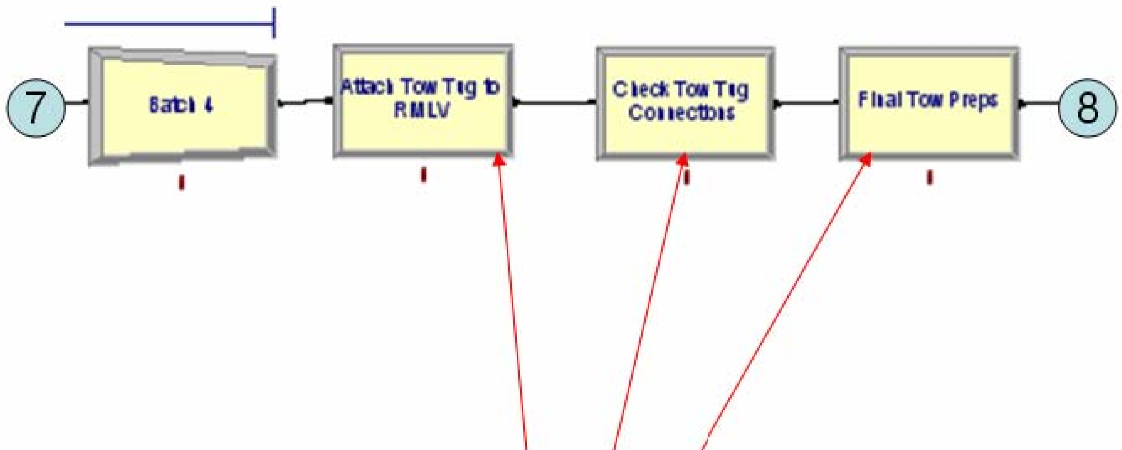
RMLV Preparation for Transportation



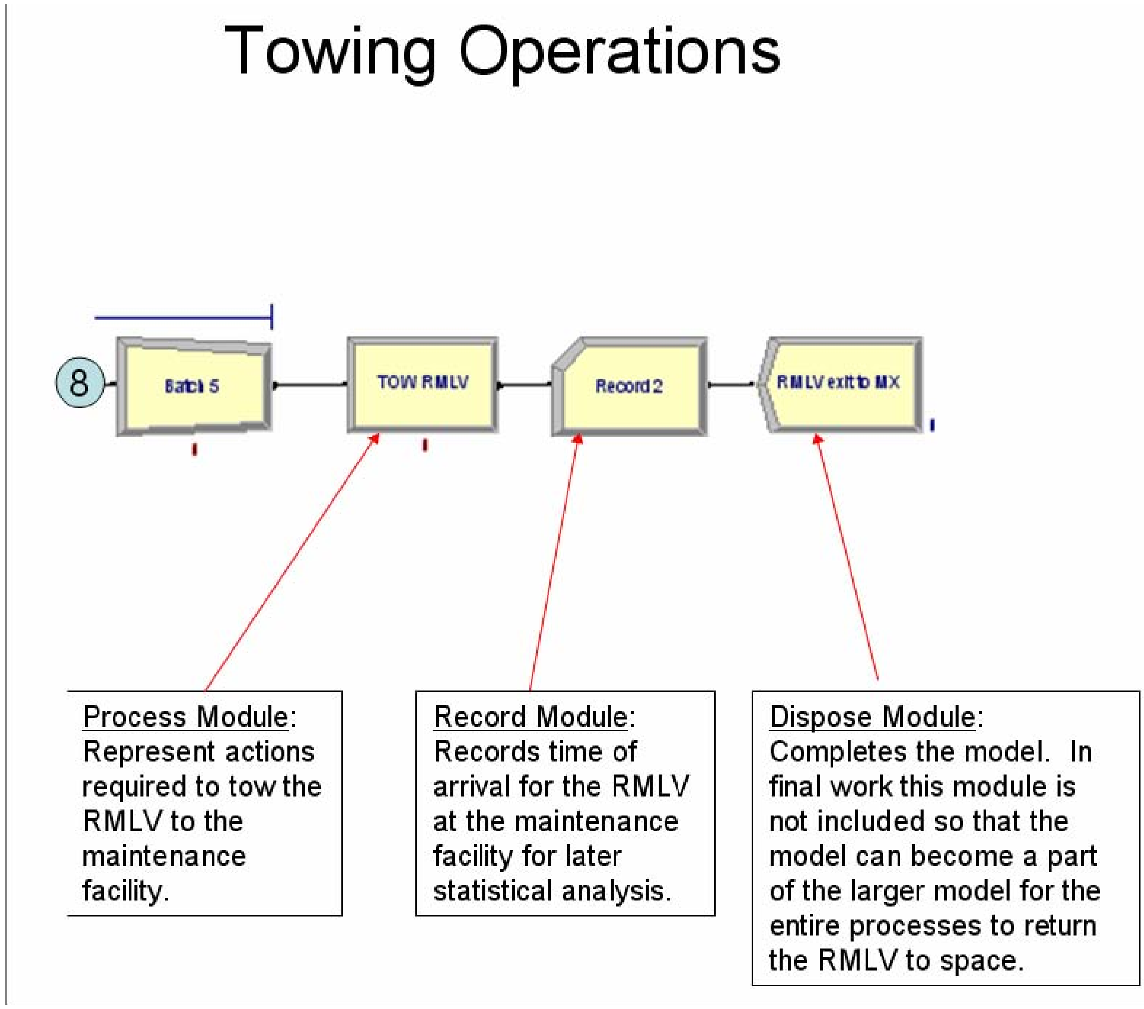
Safing Sequence



Final Tow Preparations

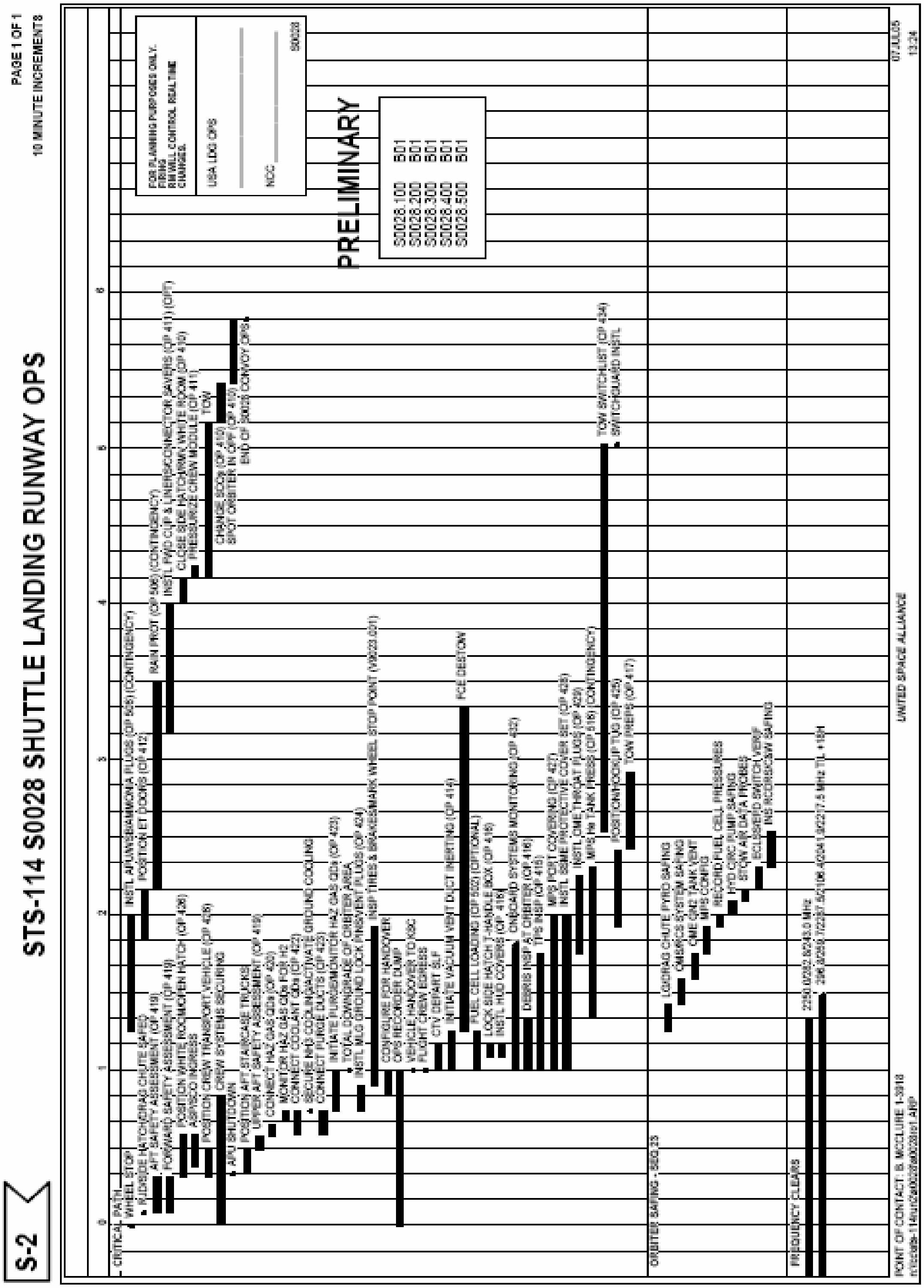


Process Modules: Represent actions required to complete tow preparations prior to transporting the RMLV to the maintenance facility.



Delphi Panel Participant Comments from Round 3

Attachment 2: STS-114 S0028 Shuttle Landing Runway Ops



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Vita

Major Michael Martindale graduated high school from St. Johns High School in St. Johns, Michigan. He earned his bachelor's of Science degree at the United States Air Force Academy, Colorado, and a Master's of Science degree in Space Studies from the University of North Dakota.

Major Martindale has served as a space operations officer at the 4th Space Warning Squadron, Holloman AFB, New Mexico, and as a missile launch officer at Minot AFB, North Dakota. He is a graduate of the Air Force Weapons School at Nellis AFB, Nevada where he also served as a weapons instructor. Major Martindale was then assigned to Headquarters Air Force, Directorate of Operations and Training, Checkmate Division, Pentagon. His deployments include support to major exercises in South Korea, Al Udeid Air Base, Qatar in support of Operation Enduring Freedom in 2001, and in again in support of Operation Iraqi Freedom in 2004. In May of 2005, he was assigned to the Air Force Institute of Technology where he earned his master's degree in Logistics Management. Upon graduation he will be assigned to the Air Force Element, Joint Chiefs of Staff, Pentagon.

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14. ABSTRACT

The purpose of this research was to develop a discrete-event computer simulation model of the post-landing vehicle recovery operations to allow the Air Force Research Laboratory, Air Vehicles Directorate to evaluate design and process decisions and their impact on RMLV regeneration time in the early phases of the acquisition process.

The model is based primarily on the post-landing vehicle recovery process for the only reusable space vehicle in the world, the Space Shuttle Orbiter. However, it does contain some elements from the aircraft recovery process for the F-16 fighter aircraft. The model was analyzed and validated by a panel of experts in the fields of Space Shuttle Orbiter and F-16 aircraft post-landing recovery. The model was verified using an assertion checking method. In addition to the model, conclusions are drawn regarding several design decision based on a comparison of the Space Shuttle orbiter and F-16 post-landing recovery operations. No experiments to evaluate design alternatives were conducted as a part of this research.

15. SUBJECT TERMS

Reusable Military Launch Vehicle, RMLV, Discrete-Event Simulation, Delphi process, Space Shuttle Orbiter, Post-Landing Recovery, Spacelift, Operationally Responsive Space

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